Psychological Monographs

Dynamics in Binocular Depth Perception

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DYNAMICS IN BINOCULAR DEPTH PERCEPTION [1]

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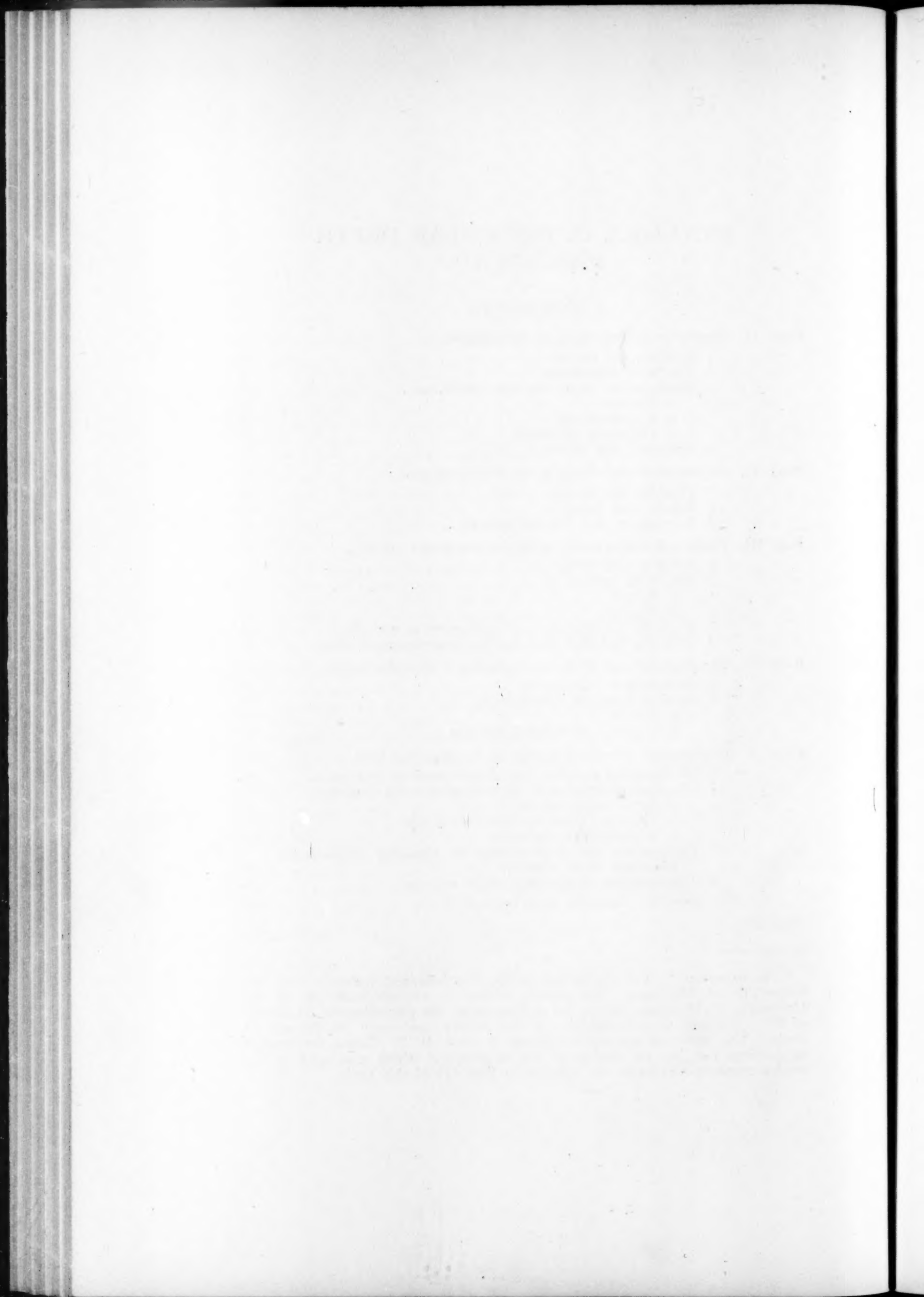
PART I

DISPLACEMENT AND DEPTH IN HALF-IMAGES

1. *The problem and its experimental set-up:*

In order successfully to analyze the process which lies at the root of binocular depth perception, it may be more profitable to work with imperfect binocular perceptions, than with stereoscopic images that are already completely developed. As in many other problems of perception, it is just those borderline cases which give us hope of arriving at a more exact knowledge of the dynamics of depth. Because of this, we have chosen, to a great extent, extreme instances of binocular vision as material for the experiments. Instead of dealing with precise stereoscopic vision, we shall concern ourselves with investigations of the Panum-phenomenon, of fragmentary images and double images, and with experiments made possible by the use of the stroboscope and the strobostereoscope.

Two basic questions confront us in the problem of depth in the double image: (a) Is the fusion of the half-images essential for genuine depth perception? (b) If it is not, on what can be based the depth effect of double images?

For a long time psychologists have replied in the negative to the first question. Both past and more recent experiments show that disunited half-images exhibit a decided aspect of depth. Indeed, the depth of the half-images can often be even more precisely defined than that of perfectly united images. If this is true, it follows that we must determine whether the perception of depth in half-images rests upon the same psychological process as the perception of depth in images that have merged together, or upon some entirely different process. It might be asked what meaning has cross-disparity and convergence-movement so far as half-images are concerned? How are these half-images, which have depth, localized in binocular space?

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The first speculations about the depth-localization of double images were made by Aguilonius [1]. According to his notions, double images have their apparent location in the plane of fixation, that is, objectively in the "horopter". Johannes Müller [2] also agrees with this hypothesis. Meissner [3] was the first to discount such an explanation. He maintained that double images have "no place at all" but that they are placed in the horopter by a process of "interpretation". Helmholtz, and particularly Hering [4], demonstrated empirically that double images do not lie in the plane of fixation, but are seen at the distance of the real object itself. Hering has also shown that, in momentary perception, the double image can be clearly localized in his "ball-dropping"-apparatus. An observer looks through the tube at a given point of fixation. A small ball is dropped across the field of vision, first in front of, and then behind, the point of fixation. The observer has no difficulty in distinguishing the relative depth of the object as it appears in a double image. As a matter of fact, the observer has an approximately accurate idea of the absolute distance of the dropped object from the point of fixation. Tschermak and Höfer [5] have carried out precise experiments dealing with this problem. The experiments were conceived in such a way that an object which appeared as a double image was judged, relative to a certain fixation point, both when momentary and continued illumination were used. The experiments gave the same positive results with symmetrical as well as with asymmetrical convergence. In a further series of experiments, in a more ingenious set-up, measurements were taken. A relatively distant point was fixed. A rod had to be shifted forwards and backwards until it seemed to be in the same frontal parallel plane with another rod, which appeared as a double image. The accuracy with which this was done was remarkable.—If the half-images be observed for some time (providing one stares continuously at one and the same fixation point), it will always be discovered that they approach closer to the fixation plane, and finally merge into it.—The relative distance from the point of fixation of a point which appears as a double image was determined by Pfeifer [6] in the following manner. F and O are two points which lie one behind the other. First O is fixed and the distance separating it from F is measured. The visual attention is then concentrated on F. The observer must judge whether the object O seen as a simple image, or O seen as a double image, is the nearer. By a clever arrangement of mirrors both these distances can be measured and compared. Pfeifer comes to the following conclusions: Double images exist neither in the depth of the fixation point, nor in the depth of the real object. Uncrossed double images are relatively farther removed in space than the object, if seen single. The same applies to crossed double images, provided that the point of fixation is at least 150 cm. removed from the observer. If the distance is less than 150 cm., the double image appears to lie at the same depth as the real object. If the distance is considerably less than

[1] Aguilonius, Franciscus, *Opticorum Libri sex. Antwerpiae*, 1613.

[2] *Zur vergleichenden Physiologie des Gesichtsinnes des Menschen und der Tiere*, Leipzig, 1826.

[3] *Beiträge zur Physiologie des Sehorgans*, Leipzig, 1826.

[4] Das Gesetz der identischen Sehrichtung, *Reicherts und DuBois Reymonds Archiv f. Anatomie u. Physiologie*, 1864, p. 44 ff. Gesetze der binokularen Tiefenwahrnehmung, *ibid.*, 1865, p. 153.

[5] Über binokulare Tiefenwahrnehmung auf Grund von Doppelbildern, *Pflügers Archiv f. Physiologie*, 1903, 98, pp. 298–320.

[6] Über Tiefenlokalisation von Doppelbildern, *Psychol. Studien*, 1907, 2, 129–202.

150 cm., it is quite likely that the observer will underestimate the depth of the double image. . . . These results of Pfeifer's cannot be easily reconciled with the conclusions of Tschermak and Höfer. We shall demonstrate that Pfeifer's results are apparently limited by the peculiar arrangement of the experimental apparatus. They do not have a universal application.

To restate once more the fundamental problem: What conditions determine the appearance of depth in the half-images? This question suggests an additional query, viz., does the half-image as such, that is, the half-image without any relation to the other eye, have depth? Hering answered in the affirmative to this problem. In order to arrive at a definite conclusion regarding this question, it is necessary to construct the experimental set-up in such a way that the impression of the one half-image a_1 made on the one eye when the corresponding half-image a_2 is missing, can be compared to the half-image a_1 when the other half-image a_2 is present for the other eye. To repeat this dis-

$$f_1 \; a_1 \quad\quad f_2 \; a_2$$
Left   Right
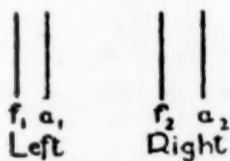
FIG. 1. General arrangement of the threads as seen by left and right eye.

tinction, the half-image a_1 seen alone must be compared with the half-image a_1 when seen together with the other half-image a_2.

The experiment proceeds in the following manner: An observer looks at two threads in such a way that one thread F is in focus, and the other thread A appears as an uncrossed double image. If the half-images are separated, they appear in different visual directions. If the cross disparity is small, so that not only f_1 and f_2, but also a_1 and a_2, merge into one, then it is obvious that the visual directions, a_1 and a_2 are identical. The visual direction a_1–a_2 takes an intermediate course relative to the monocular directions a_1 and a_2 considered individually. In other words, there is a *"displacement"* of visual direction in the half-images, which goes so far as to produce an identity of direction.

Throughout this work, the term "displacement" will be used only to indicate a change of direction of a point in the optical

field without a change of the relative position of the stimulus in the (monocular) retinal field.

If the depth effect of a disunited double image is of the same nature as the depth effect of a united double image, it may be assumed that there is a displacement òf the visual direction of half-images which are separate, relative to monocular visual direction. Such a displacement can be measured in the following way:

Let F and A stand in the same plane of fixation, in which case the visual directions a_1 and a_2 are identical. The same applies to f_1 and f_2. The points a_1 and a_2 fall on strictly corresponding points on the retina. This means that they are points which are

Figs. 2, 3, showing 2 positions of mark s_2 which may correspond with a_1.

removed an approximately equal distance from the points f_1 and f_2. Supposing now that a_1 and a_2 are separate, disunited double images. (Fig. 2.) If the visual direction of a_1, as it appears together with a_2, is different from the purely monocular visual direction of a_1, this difference should be revealed by the fact that the points in the other retina which strictly correspond to a_1 (position I) no longer maintain binocular identity with a_1. There will be other points in the second retina (position II) which are now congruent with a_1. Such displacement of the visual direction of a half-image can be measured by defining the congruent points in the retina of the other eye. Corresponding points of this kind are determined by the use of the so-called nonius-method. If a point is to be discovered in the other retina which corresponds to the point a_1, a mark s_2, which is present only in the other retina, is moved about until it coincides with a_1 in the binocular field. The combined image looks like Fig. 3.

The following experiment proves by the nonius-method

whether the half-images in the binocular field change their visual
direction, and also whether there is a relation between such a
displacement and the depth effect of the half-images. The
experiment reveals, still further, whether it is because of the
presence, over against the absence, of the half-image in the other
eye that the visual direction is influenced.

Experimental set-up: The basic procedure is as follows: The
observer, having his head held by means of a biting board and
a head-frame in a fixed position, looks through an aperture at
two black silk threads which are stretched vertically against a
white background in the " thread-apparatus ". The left thread
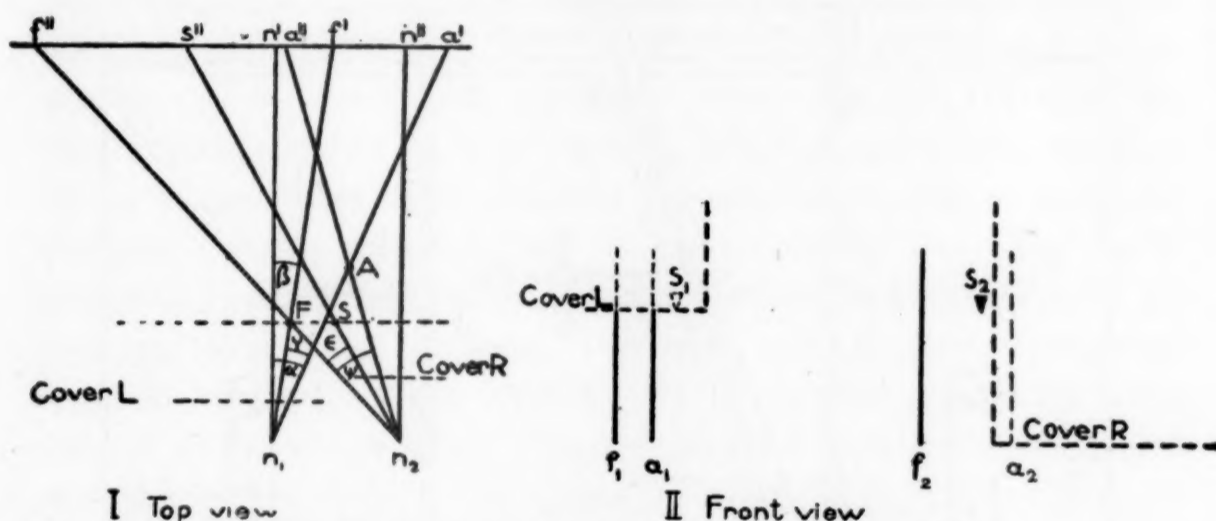
I Top view   II Front view
FIGS. 4, 5, showing the set-up at the thread-apparatus.

is farther forward. The observer focuses on this thread. The
right hand thread being farther behind appears, therefore, in
uncrossed half-images.

Explanation of Fig. 4. The two nodal points are designated
by n. F is the left, forward thread (focus). A is the right
hand thread which appears in uncrossed half-images (a_1 and a_2).
The visual angles which the left hand line makes with the right
hand line are γ and ψ respectively. In the plane of fixation, the
signal S is movable. The visual field of the left eye (Fig. 5) is
covered in the upper part by a white screen (cover L). At the
same time the screen covers the signal S for the left eye. The
right eye, on the other hand, sees S as s_2. By covering and
uncovering with the shield R the right hand half-image of the

silk thread A, that is, a_2, is alternately blotted out and revealed. O can control the strong fixation of F every time. This is shown by the fact that the uppermost part of f_2 lies precisely on the extension of f_1. The conditions of these experiments are as follows: The point in the other eye which corresponds to a_1 has to be found by moving the signal S until the point s_2 coincides with a_1 in the binocular field. Every change in the visual direction of a_1 is reflected in the changed position of s_2.

At this point we shall give a short description of the thread apparatus (Fig. 6).

FIG. 6. Thread Apparatus.
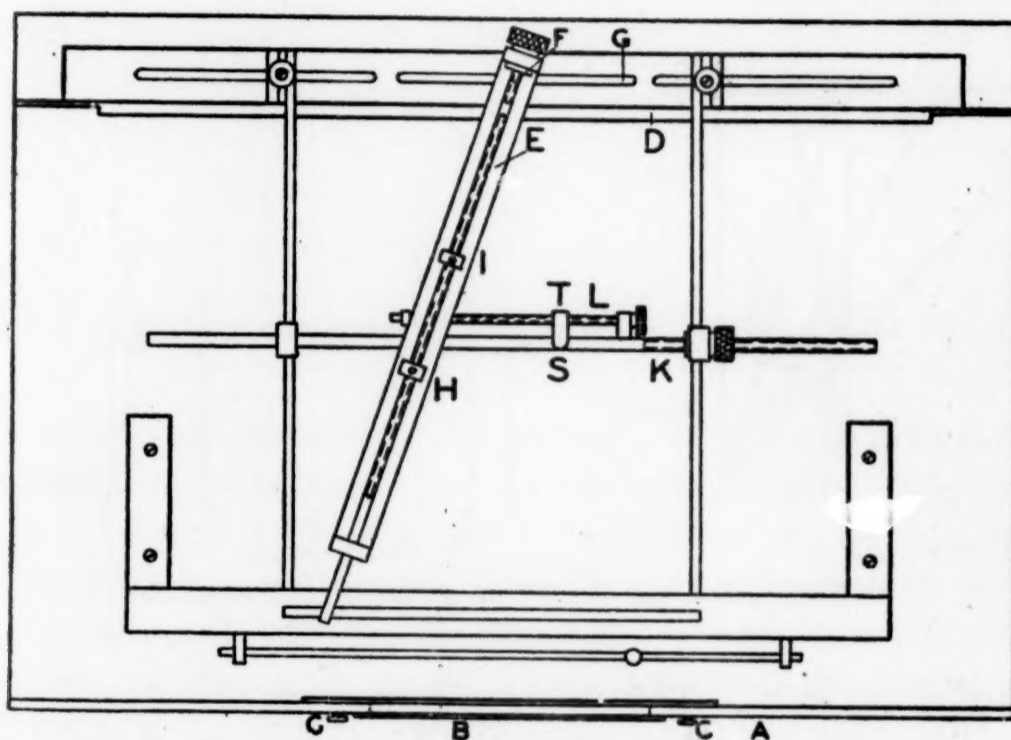
A, black screen (735 x 375 mm.); window B (200 x 75 mm.) opening of of window regulated by adjustment C (height of opening normally 10 mm.)

D, white screen; distance between white and black screen 430 mm.

E, square rod which can be turned about axis F; F is movable in slit G (at a distance of 330 mm. from base of the apparatus).

H, I, two blocks, movable in a slit along rod E; two threads of black silk (d. .006″) are attached to the blocks. To the free ends of the threads are fastened conically shaped weights of metal which drop into an oil solution to prevent oscillation.

K, coarse adjustment of mark S.

L, fine adjustment of mark S: micrometer screw for moving the block T to which is attached the mark S; adjustment of S up to .05 mm. The small, inverted black triangle, that is, the mark S, moves at a distance of 235 mm. from the black screen at a height of 240 mm. from the base.

2. *The basic experiment:*

The influence of the one half-image on the other half-image with respect to visual direction and depth effect:

The observer focuses thread F in the manner described previously. Two diverse series of experiments are carried out. In both groups of experiments, a_1 (that is, the left half-image of A) is visible. In the first group of experiments the half-image a_2 is not visible since it has been eliminated by covering it with R. In the second series of experiments, on the contrary, a_2 can be seen. In both series the average position of a signal, s_2, visible to the right eye, is determined when this position coincides with the visual direction of a_1. In other words, the visual direction of the left half-image a_1 will be determined—in the absence or presence of a_2—by finding a position of the signal in the right eye that corresponds to a_1. If there is a difference in the position of s_2 under these two different conditions, it means that the position of the half-image a_1 is influenced by the other half-image a_2.—Each single value that appears in the tables is an average taken from 20 trials. In every trial the correspondence was determined by the shifting of the signal, from the plus as well as the minus side. The duration of each observation was not objectively limited, but in no instance did it last much more or much less than 2 seconds. The variability of the single values cannot be disregarded, but it was never so great that an average could not be taken. All positions are empirically determined in terms of visual angles.[7] The visual angle ϵ, that is, the right hand visual angle between F and the signal s_2 which coincides with the left hand distance $f–a_1$ in the binocular field, represents a measure for the change in the visual direction of a_1.

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[7] The empirical determination of the different visual angles was done in the following manner (vid. Fig. 4) : n', n" are points which are projected under an angle of 90° from the nodal points upon a screen. F and f', A and a' are congruent points for the left eye. The visual angle AF (left eye) is $\angle \gamma \cdot \gamma = \alpha - \beta$. $\angle \alpha$ can be determined by means of the known distances n'a' and n_1n'.—$\tan \alpha = \dfrac{n'a'}{n_1n'} \cdot \tan \beta = \dfrac{n'f'}{n_1n'}$. The visual angle of AF (right eye)$=\angle \psi$; it can be determined in an analogous manner. The same procedure can be applied for measuring the right visual angle FS$=\epsilon$.

TABLE I

SHOWING THE INFLUENCE OF THE RIGHT HALF-IMAGE UPON THE SPACE VALUE OF THE LEFT

Space Value of left half image measured by a corresponding sign S ($\angle\epsilon$).

Subject W.   Distance of nodal points: 65.5 mm.
Distance of nodal line from fixation plane: 677.5 mm.

Constellation	Visual angle FA Left eye $\angle\gamma$	Right eye $\angle\psi$	Median visual angle FS=ϵ of right eye: Right half image a_2 lacking $\angle\epsilon_1$	present $\angle\epsilon_2$	Difference $\angle\epsilon_1-\angle\gamma$	Difference $\angle\epsilon_2-\angle\gamma$	Difference $\angle\epsilon_2-\angle\epsilon_1$
I₁	0° 19′ 31″	0° 37′ 0″	0° 19′ 55″	0° 29′ 57″	+0° 0′ 24″	0° 10′ 26″	0° 10′ 2″
I₂	0° 26′ 50″	0° 51′ 10″	0° 26′ 40″	0° 34′ 47″	—0° 0′ 10″	0° 7′ 57″	0° 8′ 7″
I₃	0° 32′ 59″	1° 4′ 55″	0° 32′ 0″	0° 38′ 0″	—0° 0′ 59″	0° 5′ 1″	0° 6′ 0″
I₄	0° 38′ 55″	1° 17′ 58″	0° 39′ 43″	0° 44′ 37″	+0° 0′ 48″	0° 5′ 42″	0° 4′ 54″
I₅	0° 44′ 44″	1° 30′ 42″	0° 44′ 40″	0° 50′ 10″	—0° 0′ 4″	0° 5′ 26″	0° 5′ 30″
I₆	0° 50′ 26″	1° 43′ 35″	0° 49′ 20″	0° 53′ 12″	—0° 1′ 6″	0° 2′ 46″	0° 3′ 52″
II₁	0° 22′ 0″	0° 37′ 30″	0° 23′ 3″	0° 30′ 28″	+0° 1′ 3″	0° 8′ 28″	0° 7′ 25″
II₂	0° 29′ 16″	0° 52′ 48″	0° 30′ 4″	0° 35′ 25″	+0° 0′ 48″	0° 6′ 9″	0° 5′ 21″
II₃	0° 36′ 36″	1° 7′ 9″	0° 35′ 25″	0° 40′ 27″	—0° 1′ 11″	0° 3′ 51″	0° 5′ 2″
II₄	0° 43′ 3″	1° 21′ 25″	0° 43′ 0″	0° 49′ 51″	—0° 0′ 3″	0° 6′ 48″	0° 6′ 51″
II₅	0° 50′ 22″	1° 35′ 32″	0° 49′ 32″	0° 55′ 48″	—0° 0′ 50″	0° 5′ 26″	0° 6′ 16″
II₆	0° 56′ 46″	1° 49′ 20″	0° 57′ 13″	1° 1′ 11″	+0° 0′ 27″	0° 4′ 25″	0° 3′ 58″
III₁	0° 23′ 37″	0° 38′ 0″	0° 23′ 27″	0° 29′ 50″	—0° 0′ 10″	0° 6′ 13″	0° 6′ 23″
III₂	0° 33′ 47″	0° 55′ 1″	0° 34′ 12″	0° 37′ 30″	+0° 0′ 25″	0° 3′ 43″	0° 3′ 18″
III₃	0° 43′ 29″	1° 12′ 0″	0° 42′ 35″	0° 45′ 33″	—0° 0′ 54″	0° 2′ 4″	0° 2′ 58″
III₄	0° 52′ 34″	1° 28′ 15″	0° 52′ 4″	0° 56′ 12″	—0° 0′ 30″	0° 3′ 38″	0° 4′ 8″
III₅	1° 0′ 14″	1° 44′ 35″	0° 59′ 53″	1° 3′ 14″	—0° 0′ 21″	0° 3′ 0″	0° 3′ 21″
III₆	1° 7′ 59″	1° 59′ 47″	1° 7′ 15″	1° 7′ 47″	—0° 0′ 44″	—0° 0′ 12″	0° 0′ 32″
IV₁	0° 28′ 34″	0° 45′ 5″	0° 28′ 59″	0° 36′ 34″	+0° 0′ 25″	0° 8′ 0″	0° 7′ 35″
IV₂	0° 40′ 40″	1° 5′ 17″	0° 40′ 22″	0° 48′ 0″	—0° 0′ 18″	0° 7′ 20″	0° 7′ 38″
IV₃	0° 52′ 35″	1° 25′ 0″	0° 52′ 3″	0° 59′ 59″	—0° 0′ 32″	0° 7′ 24″	0° 7′ 56″
IV₄	1° 4′ 25″	1° 44′ 58″	1° 4′ 56″	1° 12′ 0″	+0° 0′ 31″	0° 7′ 35″	0° 7′ 4″
IV₅	1° 16′ 2″	2° 3′ 10″	1° 15′ 48″	1° 24′ 0″	—0° 0′ 14″	0° 7′ 58″	0° 8′ 12″
IV₆	1° 27′ 48″	2° 21′ 5″	1° 28′ 12″	1° 30′ 50″	+0° 0′ 24″	0° 3′ 2″	0° 2′ 38″

Subject G.   Distance of nodal points: 65.48 mm.
Distance of nodal line from fixation plane: 677.0 mm.

Constellation	Visual angle FA Left eye $\angle\gamma$	Right eye $\angle\psi$	Median visual angle FS=ϵ of right eye: Right half image a_2 lacking $\angle\epsilon_1$	present $\angle\epsilon_2$	Difference $\angle\epsilon_1-\angle\gamma$	Difference $\angle\epsilon_2-\angle\gamma$	Difference $\angle\epsilon_2-\angle\epsilon_1$
I₁	0° 19′ 27″	0° 34′ 13″	0° 20′ 0″	0° 23′ 27″	+0° 0′ 33″	0° 4′ 0″	0° 3′ 27″
I₂	0° 25′ 29″	0° 48′ 10″	0° 25′ 10″	0° 30′ 2″	—0° 0′ 19″	0° 4′ 33″	0° 4′ 52″
I₃	0° 30′ 45″	1° 1′ 3″	0° 30′ 8″	0° 34′ 8″	—0° 0′ 37″	0° 3′ 23″	0° 4′ 0″
I₄	0° 35′ 55″	1° 14′ 1″	0° 34′ 46″	0° 37′ 20″	—0° 1′ 9″	0° 1′ 25″	0° 2′ 34″
I₅	0° 40′ 57″	1° 26′ 45″	0° 39′ 16″	0° 40′ 47″	—0° 1′ 41″	—0° 0′ 10″	0° 1′ 31″
I₆	0° 45′ 52″	1° 38′ 57″	0° 44′ 50″	0° 45′ 33″	—0° 1′ 2″	—0° 0′ 19″	—0° 0′ 43″

TABLE I—*Continued*

Constellation	Visual angle FA Left eye ∠γ	Right eye ∠ψ	Median visual angle FS=ε of right eye: Right half image a₂ lacking ∠ε₁	present ∠ε₂	Difference ∠ε₁−∠γ	Difference ∠ε₂−∠γ	Difference ∠ε₂−∠ε₁
II₁	0° 21′ 0″	0° 36′ 18″	0° 21′ 5″	0° 24′ 16″	+0° 0′ 5″	0° 3′ 16″	0° 3′ 11″
II₂	0° 28′ 24″	0° 51′ 39″	0° 28′ 4″	0° 32′ 13″	−0° 0′ 20″	0° 3′ 49″	0° 4′ 9″
II₃	0° 35′ 45″	1° 6′ 45″	0° 35′ 14″	0° 38′ 12″	−0° 0′ 31″	0° 2′ 27″	0° 2′ 58″
II₄	0° 42′ 35″	1° 20′ 59″	0° 41′ 18″	0° 44′ 36″	−0° 1′ 17″	0° 2′ 1″	0° 3′ 18″
II₅	0° 49′ 3″	1° 35′ 14″	0° 48′ 17″	0° 49′ 37″	−0° 0′ 46″	0° 0′ 34″	0° 1′ 20″
II₆	0° 55′ 13″	1° 49′ 17″	0° 55′ 37″	0° 55′ 22″	+0° 0′ 24″	0° 0′ 9″	−0° 0′ 15″
III₁	0° 22′ 42″	0° 37′ 47″	0° 23′ 14″	0° 28′ 45″	+0° 0′ 32″	0° 6′ 3″	0° 5′ 31″
III₂	0° 32′ 5″	0° 54′ 75″	0° 33′ 14″	0° 37′ 13″	+0° 1′ 9″	0° 5′ 8″	0° 3′ 59″
III₃	0° 42′ 8″	0° 12′ 10″	0° 41′ 18″	0° 48′ 3″	−0° 0′ 50″	0° 5′ 55″	0° 6′ 45″
III₄	0° 51′ 28″ 2	1° 28′ 25″	0° 49′ 58″	0° 56′ 3″	−0° 1′ 30″	0° 4′ 35″	0° 6′ 5″
III₅	0° 59′ 7″	1° 43′ 54″	0° 59′ 5″	1° 2′ 4″	−0° 0′ 2″	0° 2′ 57″	0° 2′ 59″
III₆	1° 6′ 14″	1° 59′ 12″	1° 6′ 48″	1° 7′ 0″	+0° 0′ 34″	0° 0′ 46″	0° 0′ 12″
IV₁	0° 28′ 22″	0° 44′ 12″	0° 29′ 3″	0° 33′ 15″	+0° 0′ 41″	0° 4′ 53″	0° 4′ 12″
IV₂	0° 40′ 38″	1° 4′ 25″	0° 40′ 2″	0° 43′ 7″	−0° 0′ 36″	0° 2′ 29″	0° 3′ 5″
IV₃	0° 52′ 30″	1° 23′ 35″	0° 52′ 5″	0° 55′ 11″	−0° 0′ 25″	0° 2′ 41″	0° 3′ 6″
IV₄	1° 4′ 15″	1° 42′ 23″	1° 5′ 25″	1° 7′ 17″	+0° 1′ 10″	0° 3′ 2″	0° 1′ 52″
IV₅	1° 16′ 0″	2° 1′ 58″	1° 15′ 3″	1° 17′ 3″	−0° 0′ 57″	0° 1′ 3″	0° 2′ 0″
IV₆	1° 27′ 30″	2° 20′ 43″	1° 26′ 20″	1° 27′ 30″	−0° 1′ 10″	0° 0′ 0″	0° 1′ 10″

Subject C.   Distance of nodal points: 62.5 mm.
Distance of nodal line from fixation plane: 672.0 mm.

Constellation	Visual angle FA Left eye ∠γ	Right eye ∠ψ	Median visual angle FS=ε of right eye: Right half image a₂ lacking ∠ε₁	present ∠ε₂	Difference ∠ε₁−∠γ	Difference ∠ε₂−∠γ	Difference ∠ε₂−∠ε₁
I₁	0° 16′ 34″	0° 34′ 12″	0° 15′ 49″	0° 21′ 0″	−0° 0′ 45″	0° 4′ 26″	0° 5′ 11″
I₂	0° 22′ 58″	0° 48′ 30″	0° 23′ 12″	0° 29′ 4″	+0° 0′ 14″	0° 6′ 6″	0° 5′ 52″
I₃	0° 28′ 56″	1° 1′ 12″	0° 30′ 2″	0° 35′ 0″	+0° 1′ 6″	0° 6′ 4″	0° 4′ 58″
I₄	0° 34′ 46″	1° 13′ 42″	0° 34′ 48″	0° 39′ 11″	+0° 0′ 2″	0° 4′ 25″	0° 4′ 23″
I₅	0° 40′ 22″	1° 26′ 15″	0° 40′ 2″	0° 43′ 0″	−0° 0′ 20″	0° 2′ 38″	0° 2′ 58″
I₆	0° 45′ 34″	1° 38′ 13″	0° 45′ 12″	0° 49′ 16″	−0° 0′ 22″	0° 3′ 42″	0° 4′ 4″
II₁	0° 20′ 22″	0° 35′ 6″	0° 20′ 3″	0° 23′ 22″	−0° 0′ 19″	0° 3′ 0″	0° 3′ 19″
II₂	0° 27′ 12″	0° 50′ 34″	0° 26′ 44″	0° 30′ 13″	−0° 0′ 28″	0° 3′ 1″	0° 3′ 29″
II₃	0° 33′ 53″	1° 5′ 24″	0° 32′ 47″	0° 37′ 21″	−0° 1′ 6″	0° 3′ 28″	0° 4′ 34″
II₄	0° 40′ 45″	1° 20′ 15″	0° 39′ 12″	0° 41′ 13″	−0° 1′ 33″	0° 0′ 28″	0° 2′ 1″
II₅	0° 46′ 55″	1° 35′ 2″	0° 46′ 34″	0° 47′ 58″	−0° 0′ 21″	0° 1′ 3″	0° 1′ 23″
II₆	0° 52′ 57″	1° 49′ 33″	0° 52′ 22″	0° 52′ 33″	−0° 0′ 35″	0° 0′ 24″	0° 0′ 11″
III₁	0° 22′ 30″	0° 37′ 18″	0° 21′ 32″	0° 26′ 5″	−0° 0′ 58″	0° 3′ 35″	0° 4′ 33″
III₂	0° 30′ 55″	0° 53′ 59″	0° 29′ 7″	0° 34′ 49″	−0° 1′ 48″	0° 3′ 54″	0° 5′ 42″
III₃	0° 39′ 20″	1° 10′ 2″	0° 38′ 22″	0° 42′ 12″	−0° 0′ 58″	0° 2′ 52″	0° 3′ 50″
III₄	0° 47′ 3″	1° 26′ 34″	0° 46′ 57″	0° 51′ 3″	−0° 0′ 6″	0° 4′ 0″	0° 4′ 6″
III₅	0° 54′ 45″	1° 41′ 44″	0° 53′ 20″	0° 56′ 5″	−0° 1′ 25″	0° 1′ 20″	0° 2′ 45″
III₆	1° 2′ 36″	1° 55′ 46″	1° 0′ 14″	1° 1′ 2″	−0° 2′ 22″	−0° 1′ 34″	0° 0′ 48″
IV₁	0° 28′ 26″	0° 42′ 43″	0° 28′ 32″	0° 33′ 31″	+0° 0′ 6″	0° 5′ 5″	0° 4′ 59″
IV₂	0° 40′ 40″	1° 3′ 14″	0° 39′ 17″	0° 44′ 57″	−0° 1′ 23″	0° 4′ 17″	0° 5′ 40″
IV₃	0° 52′ 22″	1° 23′ 0″	0° 52′ 12″	0° 57′ 32″	−0° 0′ 10″	0° 5′ 10″	0° 5′ 20″
IV₄	1° 3′ 2″	1° 41′ 49″	1° 1′ 2″	1° 8′ 16″	−0° 2′ 0″	0° 5′ 14″	0° 7′ 14″
IV₅	1° 14′ 25″	2° 0′ 32″	1° 14′ 22″	1° 16′ 52″	−0° 0′ 3″	0° 2′ 27″	0° 2′ 30″
IV₆	1° 25′ 44″	2° 18′ 57″	1° 24′ 59″	1° 25′ 16″	−0° 0′ 45″	0° 0′ 28″	0° 0′ 17″

The results are brought together in the tables (pp. 8 and 9). Three trained observers took part in this basic experiment. The whole investigation entailed the use of 24 diverse constellations of threads. Six constellations belong to one " group " insofar as the horizontal rod of the thread-apparatus on which they were hung was kept for each group at a constant angle relative to the median plane. The variations within each group are accounted for by the fact that in each of the six constellations the right hand thread changed its position, the difference between the successive distances $A F$ being the same, e.g., 20 mm. In the group composed of six separate constellations, the first constellation had the shortest distance between F and A, and the sixth and last constellation had the greatest distance. On technical grounds it was not possible to bring all three O's in exactly the same position with respect to the threads, although this is of no consequence so far as the results of the experiments are concerned. The variations are due to differences in the interpupillar distances of the different O's, and to the differences in the distance which separate the nodal points for the three O's from the threads. These, however, are constant variations which, for all practical purposes, can be disregarded.

Discussion of the results of the basic experiment:

A review of the various single results of these investigations shows that, in the majority of cases, the half-image a_1 of the left eye, when it was seen *alone,* had a *different space-value* in the binocular field than when it was seen *together* with the half-image of the right eye. The half-image a_1, as seen without a_2, may be called the " isolated half-image "; and the half-image a_1, as seen together with its counterpart, may be called the " joint half-image ". If the disparity between the half-images is not too great, the joint half-image appears to be a greater distance removed from the point of fixation than the isolated half-image. If, for example (vid. Table I, Subject W., Constell. I_1), two threads are taken so that the visual angle for the left eye is $0° 19' 31''$, and for the right eye is $0° 37' 0''$, then the point in the right eye which corresponds to the isolated half-image of the

left eye is seen at an angle of $0° 19' 55''$. This means that the half-image a_1 appears in the binocular field at a distance from F which is about equal to the distance exhibited by a binocular constellation in which the two threads are united to the left and the right, and have the same visual angle. Such a case is one in which both threads are presented approximately in the plane of the horopter. However, the point in the right eye which corresponds to the joint half-image in the left, has another value, that is, $0° 29' 57''$. This indicates that the half-image a_1 of the left eye is now congruent with a point in the right eye that is farther removed from F than would be the case if A lay in the plane of the horopter. The half-image a_1 actually has changed its directional value (width) under the influence of the added half-image a_2. Indeed, a_1 seems to have moved towards the direction of a_2 (Fig. 7).
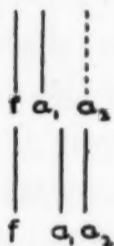
Fig. 7. Position of a_1 in the binocular field (a_2 present or lacking).
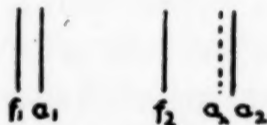
Fig. 8. a_1 and a_x related points in case II.

The directional value of the joint half-image a_1 is of the same nature as if this image had been united with a disparate image a_x in the right retina (Fig. 8).

If a_x were a real image, then the combined image a_1a_x would be seen behind the plane of fixation according to the stereoscopic laws. In other words, *there appears a displacement of the left half-image a_1 under the influence of a_2. This is analogous to the displacement which occurs during a fusion of disparate images a_1a_x. The impressions of depth made by the united disparate images a_1a_x and that made by these joint half-images a_1a_2 are also similar. Isolated half-images are seen at approximately the same depth as the line of fixation. The joint half-images are usually seen at a pronounced depth.*

The above are statements of general application. In individual cases there are exceptions to the general rule. It is an interesting fact that isolated half-images are seen either somewhat in front of the line of fixation, or somewhat behind it, or coinciding with it. Joint half-images, on the other hand, are *never* seen in front of the line of fixation, and seldom seen at a depth which coincides with it. A more precise comparison of the records of the experimental results which have a bearing on the relation between the impression of depth and displacement is given below.

Space value of isolated half-images and depth value: It will be found on inspection that values for the angle ϵ_1 vary with respect to the corresponding values for the visual angle γ. Very often they are approximately the same, sometimes slightly larger, and in some cases they are decidedly smaller. If the signal s_2 is to correspond to a left half-image of the thread (a_1) in the right eye (vid. Fig. 2–5) then, in accordance with binocular laws, when there is a complete, or approximate, equality of γ and ϵ, the line a_1–a_x (Fig. 8) should be seen in the same plane as F. If ϵ_1 is less than γ, the line a_1–a_x should be in front of the line of fixation. If ϵ_1 is greater than γ, this line should be seen behind the plane of fixation. As we have remarked, the normal case is one in which ϵ_1 and γ have about the same values. It naturally follows from this that normally the half-image appears in the plane of fixation. Those cases in which the half-image a_1 appears somewhat behind F are rather hard to account for on theoretical grounds. It is possible there are "empiric" factors which must be taken into consideration. (A actually is behind F.) There are, however, more interesting cases where there is a reversion of the actual situation, *i.e.*, a_1 appears to be somewhat in front of F. If the instances are collected in which the observers report that "a_1 is in a position decidedly in front of F", one finds some illuminating results. In 1,440 trials there were 250 examples of just such a situation. If the values obtained in the trials are inspected, it will be found that, in 200 of those 250 trials, ϵ_1 is smaller than γ. These results support the conclusion that there is a correlation between *a shortening of the apparent distance F–a_1* in the binocular field and *a reversion of*

the depth effect. The grounds for the displacement of the isolated half-image and the consequent reversed depth effect will be discussed later.

Displacement with respect to disparity: The values in our tables which show the displacement of the joint half-image a_1 under the influence of the other half-image vary remarkably for the different constellations. They also vary within the same constellation. The variations are so great that the average values can have no decisive quantitative meaning. They serve to indicate, however, that there is such a qualitative factor as displacement. Despite the incompleteness of quantitatively precise data,—a condition which is unavoidable because of the very nature of this kind of perception,—we believe that there are several definite conclusions to be drawn from the figures in the tables. (1) If in any one constellation (I, II, III, IV) the objective disparity between the two half-images increases, the relative displacement (relative, that is, to the angle γ) decreases. On the average, each series has a greater displacement at the beginning (*e.g.*, I_1, I_2 . . . .) than at the end (*e.g.*, I_5, I_6). (2) The relation between disparity and displacement can be seen even better in the following comparison. If the constellations I and II are compared with constellation IV, there will be found here and there a series of γ-angles which are approximately of like value. *E.g.*, Constellation II_2, γ=0° 29′ 16″. . . . . Constellation IV_1, γ=0° 28′ 34″. These angles correspond to the ψ angles: II_2, ψ=0° 52′ 48″; IV, ψ=0° 45′ 5″. The γ angles and the ψ angles of series I and II indicate a much greater disparity than the angles γ and ψ of series IV. What, then, is the displacement, if one compares the γ-angles which are practically the same size, but which have markedly different disparity values (ψ–γ)? In the following table II the γ-angles are given with the displacements for Constellations I and II, as over against the values for similar angles γ of series IV.

We may extract the following information from a comparison of Constellations I and II with Constellation IV: In all cases (with the possible exception of IV_1) it is those constellations whose half-images exhibit objectively a not too great disparity

TABLE II

Showing Relation Between Displacement and Disparity

S.W.

Constell. I a. II (γ)	Displacement ($\epsilon_z-\gamma$)	Constell. IV (γ)	Displacement ($\epsilon_z-\gamma$)
19' 31"	10' 26"		
22' 0"	8' 28"		
26' 50"	7' 57"		
29' 16"	6' 9"	28' 34"	8' 0"
32' 59"	5' 1"		
36' 36"	3' 51"		
38' 55"	5' 42"		
43' 3"	6' 48"	40' 40"	7' 20"
44' 44"	5' 16"		
50' 22"	5' 26"		
50' 26"	2' 46"		
56' 46"	4' 25"	52' 35"	7' 30"

S.G.

Constell. I a. II (γ)	Displacement ($\epsilon_z-\gamma$)	Constell. IV (γ)	Displacement ($\epsilon_z-\gamma$)
19' 27"	4' 0"		
21' 0"	3' 16"		
25' 29"	4' 33"		
28' 24"	3' 49"	28' 22"	4' 53"
30' 45"	3' 23"		
35' 45"	2' 27"		
35' 55"	1' 25"	40' 38"	2' 29"
40' 57"	—0' 10"		
42' 35"	2' 1"		
45' 52"	—0' 19"		
49' 3"	0' 34"		
55' 13"	0' 9"	52' 30"	2' 41"

S.C.

Constell. I a. II (γ)	Displacement ($\epsilon_z-\gamma$)	Constell. IV (γ)	Displacement ($\epsilon_z-\gamma$)
16' 34"	4' 26"		
20' 22"	3' 0"		
22' 58"	6' 6"		
27' 12"	3' 1"	28' 26"	5' 5"
28' 56"	6' 4"		
33' 53"	3' 28"		
34' 46"	4' 25"		
40' 22"	2' 38"	40' 40"	4' 17"
40' 45"	0' 28"		
45' 34"	3' 42"		
46' 55"	1' 3"		
52' 57"	—0' 24"	52' 22"	5' 10"

relative to one another which are remarkable for a higher degree of displacement in the joint half-image a_1. It may be concluded from this fact that the influence of one half-image a_2 on the displacement of the other half-image a_1 depends on the relative distance separating the two half-images. Generally speaking, that is to say, under constant conditions (strict fixation of F), the nearer the half-images are to one another, the greater the influence of one half-image in the displacement of the other. This may be called the " Law of Proximity ".

Direction of displacement and direction in depth: The results of the experiments show that in disunited half-images there is a close correlation between depth and displacement. In those cases in which a genuine displacement fails to appear, *i.e.*, especially in the case of isolated half-images, the relative depth value is near zero. As the result of a careful observation of the O's there is a distinctly visible variation in the width value of the half-images of a constant constellation concurrent with a variation in depth. One understands displacement to mean that there is an increase in the distance Fa_1 together with an increase in the depth value of the half-image. Without going into the question of the causal relation between displacement and depth, it is evident that this relation, so far as it concerns *direction,* is the same as that which exists in completely united, binocular half-images. If a_1f_1 and a_2f_2 are half-images of the left and right eye respectively, it appears that, in the binocular field, the directional value a_1 is shifted towards a_x, and the directional value a_2 towards a_y; this displacement is paralleled by the depth effect. The displacement approaches the limit of a full binocular unity, at which point $f_xa_x = f_ya_y$ (Fig. 9). In the binocular field, a_1 and a_2 appear to be so strongly influenced that they now lie in the same visual direction, and are seen as a single line. The displacement, in this case, occurs in a temporal direction in both retinas. If A is in front of F, the displacement is nasal. Temporal displacement signifies a position in front of, nasal displacement behind,

In every day life, when eye-movements are allowed to operate freely, double images of relatively great disparity will show much higher displacement and depth than they do in this experiment. Compare the experiments on the effect of eye-movement.

the fixation plane. Now, if the half-images remain separate, it is proved by the experiments that *displacement in the left eye towards the temporal side under the influence of the right half-image is paralleled by a backward depth movement.* It is unnecessary to prove that with *a displacement of the half-image nasally, there will appear a corresponding movement forward.* It is on this basis that we can explain the reversion of the depth effect which, as we have previously noted, occurs under certain conditions. These conditions are: (1) a_1 is isolated, (2) the isolated half-image exhibits a reversed displacement, that is, in

FIG. 9. Diagram showing (temporal) displacement.

the direction of F. Now, this kind of depth effect is analogous to the so-called Panum effect. In the Panum effect the observer sees two lines to the left, and one line to the right. Later we shall describe more precise experiments dealing with the depth effect in Panum constellations. At this point we may remark that the most likely basis for the displacement and its accompanying reversed depth effect is the fact that the left half-image a_1 again, in this case, comes under the influence of a half-image of the right eye, although it cannot be a_2, since a_2 is not present. The effective half-image is here f_2. The displacement of a_1 is directed towards F and therefore is *nasal.* As it has been said before, a nasal displacement is accompanied by a depth movement *forward.* This explains the apparent anomaly that a_1, which one would expect to see farther behind the plane of fixation,

actually moves farther in front of the plane, depending on the extent of the influence of f_2, that is, depending on the nasal displacement.

3. *Experiments concerning displacement under varying conditions:*

The following investigations describe the different conditions under which the displacement and the depth effect vary in constellations that remain equal.

(a) *Displacement with respect to attitude:* If the disparity between the half-images is neither too great, nor too small, it is

TABLE III

SHOWING THE DIFFERENCE IN DISPLACEMENT OF LEFT HALF IMAGE IN CASE OF UNIFIED VS. NOT UNIFIED DOUBLE IMAGES

S_2 (right; $\angle \epsilon$) corresponds to a_1 (left).

Constellation	Visual angle FA		Visual angle FS$=\epsilon$ of right eye: Both half images	
	Left eye	Right eye	Unified (ϵ_3)	Not unified (ϵ_2)
I_1	0° 19′ 31″	0° 37′ 0″	0° 35′ 27″	0° 29′ 57″
I_{1-2}	0° 23′ 15″	0° 44′ 15″	0° 41′ 56″	0° 33′ 10″
I_2	0° 26′ 50″	0° 51′ 10″	0° 47′ 12″	0° 34′ 47″
II_1	0° 22′ 0″	0° 37′ 30″	0° 34′ 12″	0° 30′ 28″
II_{1-2}	0° 25′ 45″	0° 43′ 30″	0° 41′ 12″	0° 33′ 45″
II_2	0° 29′ 16″	0° 52′ 48″	0° 48′ 3″	0° 35′ 25″
III_1	0° 23′ 37″	0° 38′ 0″	0° 36′ 1″	0° 29′ 50″
III_{1-2}	0° 28′ 42″	0° 46′ 12″	0° 43′ 40″	0° 33′ 40″
III_2	0° 33′ 47″	0° 55′ 1″	0° 52′ 20″	0° 37′ 30″
IV_1	0° 28′ 34″	0° 45′ 5″	0° 41′ 45″	0° 36′ 34″
IV_{1-2}	0° 34′ 43″	0° 55′ 18″	0° 52′ 2″	0° 40′ 55″
IV_2	0° 40′ 40″	1° 5′ 17″	1° 1′ 0″	0° 48′ 0″

possible, as Helmholtz, Hering, and Hillebrand all knew,[8a] that the half-images will alternately unite and separate. It is assumed that the focus-line is sharply fixed, and that the period of fixation does not last too long. In this event, the binocularly united image is more sharply defined in its depth than the double image. This corresponds to the fact that the displacement of a_1 appears to be greater in the case of the united image than in the case of the double image. The table III contains a sample out of a series of experiments.

It is clear that the angle ϵ_3 (of a unified image), as in the case of the angle ϵ_2, will vary, generally speaking, between a maximum

[8a] F. Hillebrand, *Lehre von den Gesichtsempfindungen.* Vienna, 1929, p. 130.

that corresponds to the value of ψ, and a minimum that corresponds to the value of γ. The higher value of the angle ϵ_3 with respect to the angle ϵ_2 is present in all cases. The size of angle ϵ_3, however, naturally never reaches the maximum of the value of ψ. This could happen only in case the left hand image a_1 were alone displaced in the binocular field. It is evident, however, that there is a displacement of the right hand image, as well as a displacement of the left. This will determine the value of the binocular image somewhere between the values for γ and ψ. Summing this up, we may say that, parallel to the higher value of the displacement of a_1, there is an increased expression of depth in the case of a binocular unification.

(b) *Displacement with respect to eye movement:* It is well known that eye movements increase the depth effect considerably in the stereoscopic perception. The explanation for this fact has always been unsatisfactory. It is especially important for the theory of depth perception that the influence of eye movement on the phenomenon of depth should be given serious study. The question of the exact amount and nature of influence exerted by eye movement on the half-image is of decided importance.

In these experiments the displacement of the left joint half-image in normal fixation was compared with the displacement of the same half-image as observed immediately after a movement of the eye. The observer was given the task of passing judgment on the correspondence between a_1 and s_2 only after he was certain that f_1, f_2 were in focus. He was to arrive at this focus F from a position in which he had previously fixed A. It was essential that the judgment be given immediately after the focus F had been reached, for a longer fixation of F would carry.the experiment over into the basic experiment which we have already described.

The values arrived at by these experiments also have no strict quantitative meaning, but they are significant insofar as they show that such an eye movement has an influence on displacement. In the following table IV the ϵ_2 values, which indicate the displacement in ordinary fixation, are placed opposite the ϵ_4

values, which refer to the displacement as conditioned by the eye movement.

The experiments yield the following unequivocal results: *When there is a voluntary movement of the eyes from the focus* A *in the direction of the focus* F, *there is an increase in the displace-*

TABLE IV

Showing the Influence of Eye Movement upon Displacement

Space value of left half image measured by a corresponding sign $S(\angle\epsilon)$ in right eye.

S.W. Constellation	Visual angle FS=ϵ Normal series	Eye-movement	S.G. Constellation	Visual angle FS=ϵ Normal series	Eye-movement
I_1	$\epsilon_2=0°\ 29'\ 57''$	$\epsilon_4=0°\ 33'\ 52''$	I_1	$\epsilon_2=0°\ 23'\ 27''$	$\epsilon_4=0°\ 29'\ 31''$
I_2	$\epsilon_2=0°\ 34'\ 47''$	$\epsilon_4=0°\ 38'\ 12''$	I_2	$\epsilon_2=0°\ 30'\ 2''$	$\epsilon_4=0°\ 35'\ 12''$
I_3	$\epsilon_2=0°\ 38'\ 0''$	$\epsilon_4=0°\ 43'\ 18''$	I_3	$\epsilon_2=0°\ 34'\ 8''$	$\epsilon_4=0°\ 40'\ 19''$
I_4	$\epsilon_2=0°\ 44'\ 37''$	$\epsilon_4=0°\ 49'\ 22''$	I_4	$\epsilon_2=0°\ 37'\ 20''$	$\epsilon_4=0°\ 40'\ 30''$
I_5	$\epsilon_2=0°\ 50'\ 10''$	$\epsilon_4=0°\ 53'\ 40''$	I_5	$\epsilon_2=0°\ 40'\ 47''$	$\epsilon_4=0°\ 42'\ 12''$
I_6	$\epsilon_2=0°\ 53'\ 12''$	$\epsilon_4=0°\ 56'\ 42''$	I_6	$\epsilon_2=0°\ 45'\ 33''$	$\epsilon_4=0°\ 47'\ 29''$
II_1	$\epsilon_2=0°\ 30'\ 28''$	$\epsilon_4=0°\ 33'\ 15''$	II_1	$\epsilon_2=0°\ 24'\ 16''$	$\epsilon_4=0°\ 29'\ 2''$
II_2	$\epsilon_2=0°\ 35'\ 25''$	$\epsilon_4=0°\ 42'\ 35''$	II_2	$\epsilon_2=0°\ 32'\ 13''$	$\epsilon_4=0°\ 36'\ 13''$
II_3	$\epsilon_2=0°\ 40'\ 27''$	$\epsilon_4=0°\ 46'\ 20''$	II_3	$\epsilon_2=0°\ 38'\ 12''$	$\epsilon_4=0°\ 42'\ 3''$
II_4	$\epsilon_2=0°\ 49'\ 51''$	$\epsilon_4=0°\ 54'\ 32''$	II_4	$\epsilon_2=0°\ 44'\ 36''$	$\epsilon_4=0°\ 50'\ 41''$
II_5	$\epsilon_2=0°\ 55'\ 48''$	$\epsilon_4=1°\ 0'\ 48''$	II_5	$\epsilon_2=0°\ 49'\ 37''$	$\epsilon_4=0°\ 54'\ 19''$
II_6	$\epsilon_2=1°\ 1'\ 11''$	$\epsilon_4=1°\ 6'\ 33''$	II_6	$\epsilon_2=0°\ 55'\ 22''$	$\epsilon_4=0°\ 59'\ 37''$
III_1	$\epsilon_2=0°\ 29'\ 50''$	$\epsilon_4=0°\ 33'\ 10''$	III_1	$\epsilon_2=0°\ 28'\ 45''$	$\epsilon_4=0°\ 31'\ 16''$
III_2	$\epsilon_2=0°\ 37'\ 30''$	$\epsilon_4=0°\ 44'\ 55''$	III_2	$\epsilon_2=0°\ 37'\ 13''$	$\epsilon_4=0°\ 32'\ 28''$
III_3	$\epsilon_2=0°\ 45'\ 33''$	$\epsilon_4=0°\ 51'\ 13''$	III_3	$\epsilon_2=0°\ 48'\ 3''$	$\epsilon_4=0°\ 50'\ 7''$
III_4	$\epsilon_2=0°\ 56'\ 12''$	$\epsilon_4=1°\ 0'\ 30''$	III_4	$\epsilon_2=0°\ 56'\ 3''$	$\epsilon_4=0°\ 59'\ 11''$
III_5	$\epsilon_2=1°\ 3'\ 14''$	$\epsilon_4=1°\ 6'\ 0''$	III_5	$\epsilon_2=1°\ 2'\ 4''$	$\epsilon_4=1°\ 4'\ 10''$
III_6	$\epsilon_2=1°\ 7'\ 47''$	$\epsilon_4=1°\ 11'\ 10''$	III_6	$\epsilon_2=1°\ 7'\ 0''$	$\epsilon_4=1°\ 10'\ 22''$
IV_1	$\epsilon_2=0°\ 36'\ 34''$	$\epsilon_4=0°\ 40'\ 12''$	IV_1	$\epsilon_2=0°\ 33'\ 15''$	$\epsilon_4=0°\ 35'\ 12''$
IV_2	$\epsilon_2=0°\ 48'\ 0''$	$\epsilon_4=0°\ 55'\ 13''$	IV_2	$\epsilon_2=0°\ 43'\ 7''$	$\epsilon_4=0°\ 47'\ 34''$
IV_3	$\epsilon_2=0°\ 59'\ 59''$	$\epsilon_4=1°\ 7'\ 5''$	IV_3	$\epsilon_2=0°\ 55'\ 11''$	$\epsilon_4=0°\ 59'\ 22''$
IV_4	$\epsilon_2=1°\ 12'\ 0''$	$\epsilon_4=1°\ 19'\ 3''$	IV_4	$\epsilon_2=1°\ 7'\ 17''$	$\epsilon_4=1°\ 11'\ 0''$
IV_5	$\epsilon_2=1°\ 24'\ 0''$	$\epsilon_4=1°\ 29'\ 32''$	IV_5	$\epsilon_2=1°\ 17'\ 3''$	$\epsilon_4=1°\ 22'\ 12''$
IV_6	$\epsilon_2=1°\ 30'\ 15''$	$\epsilon_4=1°\ 34'\ 41''$	IV_6	$\epsilon_2=1°\ 27'\ 30''$	$\epsilon_4=1°\ 31'\ 58''$

ment. In unique cases the displacement can be so great that there is a complete unification of both threads where, ordinarily, there would be seen only double images.[8b] However the theory of depth perception may explain this phenomenon, this much, at least, seems certain: the increase in displacement depends upon the fact that, during movement, the separation of the united, or

[8b] In agreement with these results are the findings of Brant Clark (An eye movement study of stereoscopic vision. *Amer. J. Psychol.*, 1936, **48**, 82–97).

nearly united, half-images a_1, a_2 occurs more slowly than the unification of the half-images f_1, f_2. *Together with this increase in displacement there goes the impression of greater depth.* More precise theoretical discussion will follow later.

(c) *Displacement with respect to objective movement:* If an object, for instance a knitting needle, is moved back and forth, there appears, as sometimes is noticed by previous investigators, an increase of depth during the movement, compared with the impression of depth at the conclusion of the movement. The relation of the objective movement to the depth process is investigated by means of the following procedure: On the horizontal bar of our thread apparatus, which is placed obliquely with
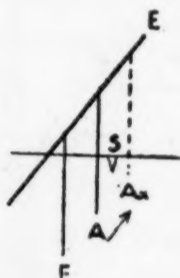
Fig. 10. Set-up for experiment where A is seen moving.

respect to the median plane, is placed the thread F, which, as in the previous experiments, hangs in a fixed position.

The thread A, which appears behind F, is moved backward by the experimenter. As before, A appears in the uncrossed half-images a_1 and a_2. The signal S, which is visible only to the right eye as the image s_2, is kept constantly fixed in one position so that during the movement of A, the half-image a_1 must at some time be covered by s_2 in the binocular field.

The figures in the table V show that, in the fixation of a thread F, if a second thread A is moved backward, the half-images a_1 and a_2 remain closer together during this movement than they did when the threads were kept permanently in one chosen position, and observed for some considerable time. Should the thread A, for example, be moved from some predetermined point (left visual angle $FA=\gamma=0°\ 37'\ 27''$; FA right$=\psi=$ $1°\ 5'\ 57''$), it will finally arrive at a position where it is part of a constellation in which the left half-image a_1 is covered by the

fixed mark s_2 ($f_2s_2 = 1° 4' 22''$). If A is kept in this position and observed continuously this correspondence is no longer valid. The point s_2 is too far to the right of a_1. In order to establish correspondence, therefore, the signal must be shifted far enough to the left so that there will be a correspondence between a_1 and s_2; $f_2s_2 = 0° 56' 20''$. The results are such that the half-image

TABLE V

Showing the Influence of Objective Movement upon Displacement

S.W. *Series I* (γ=visual angle FA of the left eye; ψ=visual angle FA of the the right eye).

Movement starts with: $\gamma = 0° 37' 27''$; $\psi = 1° 5' 57''$

	The one extreme constellation FA_x:	The other extreme constellation FA_y:
Monocular left visual angle f_1a_1:	0° 56' 8"	1° 0' 50"
Right visual angle f_2s_2: movement: (s₂ corresponds to a₁)	1° 4' 22"	1° 4' 22"
Right visual angle f_2s_2: fixation during rest:	0° 56' 20"	1° 0' 60"
Difference of displacement: movement vs. rest:	0° 8' 2"	0° 3' 22"

Series II   Movement starts with: $\gamma = 0° 45' 33''$; $\psi = 1° 18' 37''$

	The one extreme constellation FA_x:	The other extreme constellation FA_y:
Monocular left visual angle f_1a_1:	1° 11' 36"	1° 15' 34"
Right visual angle f_2s_2: movement:	1° 27' 10"	1° 27' 10"
Right visual angle f_2s_2: fixation during rest:	1° 11' 17"	1° 15' 12"
Difference of displacement: movement vs. rest:	0° 15' 53"	0° 11' 58"

Series III   Movement starts with: $\gamma = 1° 1' 3''$; $\psi = 1° 28' 23''$

	The one extreme constellation FA_x:	The other extreme constellation FA_y:
Monocular left visual angle f_1a_1:	1° 56' 20"	2° 2' 0"
Right visual angle f_2s_2: movement:	2° 13' 43"	2° 13' 43"
Right visual angle f_2s_2: fixation during rest:	1° 56' 10"	2° 2' 12"
Difference of displacement: movement vs. rest:	0° 17' 33"	0° 11' 31"

of A, which has moved into the position A_x, exhibits a greater displacement than in case it is observed briefly afterwards, while at rest. (Since the disparity in the constellations used is very great, the displacement in the case of rest is not far from 0: the points a_1 and s_2 fall on points that very nearly correspond: in our case, $f_1a_1 = \gamma = 0° 56' 8''$ and $f_2s_2 = \psi = 0° 56' 20''$).

Bringing all these facts together, we are able to say that *an object moving through any position is characterized by an*

increase in the displacement of its half-images, as compared with the object kept permanently at that position. With this increase in the displacement, there appears an increase in the depth effect. The direction of displacement corresponds to the direction of the depth. This means that since, in our case, the displacement is marked by an increase in the temporal direction, the depth effect will undergo a strengthening in the backward direction. (If the displacement is approximately 0, the depth effect must also have approximately the value of 0. The observer steadily sees the half-image of the fixed thread, after a brief preliminary period, almost in the plane of fixation. As soon as the fixation of F is complete, and has continued for some time, the half-image a_1 appears to be nearly altogether in the plane of fixation in consequence of the too large disparity.)

It seems to be, then, that movement conditions the visual area in such a way that a higher displacement results, and, together with this, a corresponding increase in the depth effect follows. These conditions of movement will be analyzed in the following theoretical investigation.

4. *Summary and theoretical discussion:*

The experiments show that neither Helmholtz's assumption of the constancy of width values in the half-images in a given constellation, nor the Hering theory of the given, innate depth values of the half-images, corresponds to the actual facts. The experiments reveal unequivocally that (1) by no means do the half-images of a given constellation have a constant width value, and that (2) the half-images do not always lie either at the depth of the object, or at the depth of the plane of fixation. It has been positively demonstrated that there is a close relation between the depth values and the displaced width values. The monocular width value of a joint half-image does not usually agree with its binocular width value. The joint half-image in the binocular field of vision is displaced relative to an image in the binocular field whose cognate image in the other eye would lie at a strictly corresponding point. It can be seen in these experiments that, all other conditions being equal, the direction and the magnitude

of displacement, and the direction and the extent of the depth effect, run parallel. This means that if there is such a displacement (it does not matter in which eye), there will follow a movement of the depth forward, providing that the displacement is nasal in direction. If the displacement is in the direction of the temporal side, the depth of the image moves backward.[9] If there is no displacement, the half-image will appear in the plane of fixation, providing, of course, that there are no (so-called empirical) factors present which are not included in a genuine, binocular interaction, with which we are concerned here.

It may be concluded, too, that the relation between displacement and the binocular perception of depth in half-images seems to be of just the same nature as it is in normal, unified, stereoscopic vision. In the normal vision there is the same movement backward, whenever there is a displacement in the temporal direction. The difference lies in the fact that, in the perception of double images, the displacement does not lead to complete unification. What does this difference indicate, so far as the physiology of the retina is concerned? In unifying binocular vision strictly corresponding points are revealed by the identity of visual directions (Hering). Furthermore, disparate, but unified, points are identical in direction; the resulting direction in this instance is, however, a median value of the visual directions of both points. Let us now assume that a *non-unified half-image* has been displaced by a binocular process. *This, logically, might be described as unification of this half-image with some disparate point in the other retina which has not been stimulated from any external source. Fundamentally, then, the vision of a double image in the binocular field would rest, too, on a unification of points in the retina.* There are, according to such a hypothesis as far as a double image is concerned, two possible kinds of unification. The retinas are united in such a way that the corresponding points cover each other. This is equivalent to saying that the seen half-image of the one eye is congruent with strictly corresponding points in the other eye

[9] Towards the " nasal side " and the " temporal side " are not to be confused with the " nasal side of the focus " or the " temporal side of the focus ". They are absolute, and not relative, directions.

which have received no stimulus. Again, there is the second possibility that the retinas are united in such a way that some points do actually fall together (the focus-line), but, on the other hand, the half-image of each eye coincides with an unstimulated disparate point in the other eye. Disparity which occurs in the case of the perfectly united double image is, according to this last view, different from that which occurs in the case of the two images seen singly. It is a disparity between points one of which has received a stimulus and one of which has not. The space value of each image, exactly as in the case of normal binocular vision, when two stimulated points are united, can be thought of as a median direction between the monocular visual direction of the half-image and the monocular direction of the point which has received no external stimulus. The greater the disparity between the stimulated and the non-stimulated related point, the nearer do the real half-images approach each other, until at last there is a full unification of half-images a_1 and a_2. And, oppositely, the smaller the disparity (displacement) between the half-image of one retina and the non-stimulated related point in the other retina, the more the real half-images a_1 and a_2 fall apart. If the half-image of one eye is united with a non-stimulated point in the other so that a strict correspondence exists, then the half-image must theoretically appear in the fixation plane. The half-image normally varies between a maximum (unification with the other half-image) and a minimum of disparity. In keeping with this whole conception, it follows that a displacement of the half-image is possible somewhere between this maximum and minimum. If the parallelism between disparity and depth perception holds still further, the half-image, because of the displacement, would have a depth of 0 at the minimum, and a maximum depth at the point of maximum displacement. Experiments with fragmentary images and other stroboscopic experiments will prove that the assumption of a relation between stimulated and non-stimulated points in both eyes is not at all without a basis in fact. This hypothesis, it will be discovered, correlates the actual facts in the simplest way possible. The next premise is, that in the double image as well as in normal binocular

perception the factor of displacement is the visual expression of the unification of disparate points on the retina.

It is altogether a separate question whether displacement, on the basis of the interdependence of retinal disparity and depth perception, is the sole and complete causal agent, which brings about the phenomenon of depth. This question will be answered further along, and will not be decided until very definite grounds have been experimentally established which can serve as a basis for a correct interpretation. Displacement, based upon disparity in the sense of Hering's theory, may be found as a necessary, but insufficient, condition for the phenomenon of binocular depth. At this stage of the general investigation, however, we may assume only this much: (1) *All other physiological conditions being equal, there will be a greater depth effect running parallel to a greater displacement.* (2) *The direction of displacement (nasal or temporal) will, ceteris paribus, parallel the direction of depth (forward or backward).*

A resumé of the general conditions governing displacement, as revealed in the preceding experiments, brings to light the following relations:

I. Objective Conditions

1. (a) Presence of a second half-image: displacement; depth corresponding to the direction of displacement.

1. (b) Absence of second half-image: displacement lacking; half-image appears approximately in the plane of fixation.

2. Presence of second half-image together with great disparity: displacement small, or lacking; depth: half-image appears close, or in the plane of fixation.

3. Objective movement: displacement greater than when at rest; depth increased and more sharply defined than at rest.

II. Subjective Conditions (both half-images present)

1. Eye-movement: displacement and depth increased relative to normal vision at rest.

2. Long fixation: displacement small, even up to 0; half-images approach the plane of fixation.

III. Special Conditions for the Isolated Half-Image

Dynamic relation to f_2 (Panum-constellation): reversed displacement.

The results presented in I are related to the basic experiment dealing with the presence of absence of the one half-image, insofar as it affects the displacement of the other half-image. It has been stated that displacement is the result of the dynamic process of unification. There is a tendency to reach such maximal degree of congruence in the retinal points that both images coincide. Displacement, therefore, arises from a tendency to change the " normal " congruence-relations of the double retina. So far as we can make out, there are two possibilities which may explain such a dynamic process. (1) Incongruence in the images is a stimulus which immediately occasions a change in space-values. By means of this stimulus, a dynamic process is introduced which supersedes " normal " congruence, and strives to arrive at a congruence that is more adequate. This assumption does not need the phenomena of eye-movement to explain it. (2) Eye-movements seek to correct incongruence. There is a tendency to fix not only point F, but also point A. Such eye-movements are not *directly* responsible for depth, but, as we know from the experiments, *indirectly* condition displacement. If A is fixed first, and the observer then quickly shifts his visual attention to F, it will be seen that, in the first instant of the unification of f_1 and f_2, a_1 and a_2 will be nearly, or completely, united. It is only after this movement that the half-images of A move distinctly apart. It can so be directly observed that the change in relative space-values of the half-images occurs more quickly with $f_1 f_2$ than with $a_1 a_2$. There is a maximum in the relative displacement between F and A at the very first moment of the fusion of $f_1 f_2$. The experiments show, therefore, that the half-images of a focused point which are seen singly tend, with a change of fixation, to remain united.

One might regard the cause of this " inertia of separation " as being of a general nature. If one recalls the fact that in every-day life objects retain their " absolute " position in the optical field during eye-movements, one is inclined to believe that the " inertia " is caused by some general mechanism by means of which the once attained direction-value of an object is kept constant. This, of course, would mean to keep the direction-value of the half images during their change on the retinas alike, *e.g.*, to keep the half images fused.

In consequence of such eye-movements, the velocity by which f_1 and f_2 become united is higher than the velocity by which the

half-images of *A* separate.   One may call this phenomenon
" velocity parallax ".

Displacement would then originate not in an original *space-parallax,* but in a *"binocular parallax of velocity".*   This theory
would, accordingly, correlate the conditions of I with the con-
ditions of II.   It can be demonstrated by means of many obser-
vations in experiments dealing with eye-movements that there is
such a " velocity parallax " in all movements of convergence and
divergence.

If the two theories which attempt to clarify the phenomenon
of displacement (that is, either an immediate relation between
disparate points: space parallax, or a mediated dynamic relation
on the basis of eye-movements: velocity parallax) are compared,
it seems that the theory of velocity parallax comprehends the
facts more adequately.   In spite of this obvious pragmatic
superiority of the second theory, I am still inclined to believe
that displacement must be accounted for not only indirectly on
the basis of eye-movements, but also on the basis of the direct
factor of incongruence.   The experimental fact that there is
depth impression as a characteristic of half-images in momentary
illumination, which of course precludes eye-movements, lends
support to such a view.   On the other hand, there is no doubt
that the eye-movements themselves add strength to the displace-
ment.   In other words, displacement by space parallax is
strengthened by time parallax (velocity parallax).   In the
experiments which we have made, it is easier to arrive at a
higher degree of displacement when there is a movement from
the fixation point *A* to the fixation point *F*, than when the fix-
ation point *F* is immediately observed.

Let us now turn to II_2.   How can one explain the fact that
there is a decrease in the displacement of the half-image, and
consequently a lessening of the depth effect, when there is a
continued fixation?   Apparently here, too, the theory of velocity
parallax might be conceded a decided advantage, for longer
fixation reduces the movements of the eye, and consequently the
possibility of a velocity parallax.   The influence of fixation
might also, however, be explained from the standpoint of an

immediate half-image dynamic.   Because of the continued fix-
ation of f_1 and f_2, the dynamic relation existing between a_1 and
a_2 becomes less and less potent.   The point a_1 increasingly falls
under the influence of the intensively perceived f_2.   Weakening
of the dynamic relation between a_1 and a_2 means, however, a
return to the conditions which determine the phenomenon of the
isolated half-image, *i.e.*, the half-image tends to appear in the
plane of fixation.   The idea just mentioned is supported by the
well-known fact that peripheral images are " drawn " towards
the attention center of a monocular field.[11]   This attraction is
directly evident in the case of excessive disparity of the half-
images.   The attraction can even become so great that the
" Panum-phenomenon " appears.   That is: the line a_1, which
originally, in dynamic relation to a_2, *appears behind* the plane of
fixation, will be displaced in the opposite direction because of its
other dynamic relation to f_2, and can therefore appear in front
of the plane of fixation.

It is easy to see that there can be no line drawn between the
two theoretical conceptions.   The decrease in displacement in
fixation may just as well be conditioned by the change in the
dynamic relation of the half-images, as by the cessation of the
eye-movements with a consequent decrease in the velocity
parallax.

Many of those who have investigated the problems of optical perception,
among them Hering and Tschermak, have remarked on the fact that there is a
lessening of the depth effect if the fixation is continued.   It has been shown in
our experiments, on the other hand, that there is an interdependence existing
between the lessening of the depth effect and a decrease of displacement in
fixation, and between the increase of depth effect and increase of displacement
in eye-movements.   Some of the results of the experiments made by A. Pfeifer
can be understood from the assumption of such an interdependence.   Pfeifer
found, as we have had occasion to remark previously, that the double image
(especially when it is uncrossed) appears at a greater depth than the unified
binocular image.   Such a result, which seems to contradict the experimental
results arrived at by Tschermak, and ours as well, must be explained, in my

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[11] Vid. the discussion by Lipp: Die Unterschiedsempfindlichkeit im Sehfeld
unter dem Einfluss der Aufmerksamkeit; *Arch. f. Psychol.*, XIX, 1910, p. 313.
Tschermak: Grundlagen der optischen Lokalisation nach Höhe und Breite;
Ergebnisse d. Physiol., IV, Abt., 2, 1905, p. 517.   Morrey, C. B.: Precision in
Eye-movements and Localisation in the Periphery of the Retina; *Journal of
Psychol.*, XX, 1899, p. 317.

opinion, by the special conditions of his experimental set-up. The situation on which the comparison was based was this: The distance OF, as fixed in O is

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FIG. 11

compared with the distance OF, as fixed in F. The point O is seen first as a single image, and later as a double image. The distance from F must be judged under both circumstances. Experimental results of general application could be gained from this procedure only in the event that all factors which determine the depth impression were present under both conditions. However, the factor of time exposure, which is a strong influence on the depth of the double images, is left entirely to the will of the observer. What is the result? The depth during a *continued period of fixation* is compared with a depth *that follows immediately after a momentary, glancing movement of the eye*. The result of such a comparison according to our own experiments, would be that the displacement for the double image O, relative to a fixation point F, is greater than the displacement of the double image F, relative to a fixation point O. Consequently FO appears to be larger in the second exposure than in the first. And that is exactly what Pfeifer found. In addition to these sources of error in a lack of experimental control of the fixation time there are other uncontrolled factors in Pfeifer's experiments such as differences in visual size, etc., which also exert a misleading influence. All that can be gained from the experiments of Pfeifer is the fact that double images have depth, and that this depth can by no means be explained away by the so-called " empirical factors ".

Discussion of I_3: The final experimental result which should be explained is the increase of displacement in case of objective movement of the thread A under fixation of F. If one sticks to the fundamental thesis of the eye-movement theory, it must be assumed that under the conditions which govern the movement of A, the eye-movements are increased, and, because of this, the velocity parallax (together with the displacement) also increases. If one tends to favor the standpoint of a direct dynamic relation between the half-images, the ground for a higher displacement will be found in an increase of the dynamic relation between a_1 and a_2. In this case it must be asked why does the dynamic tendency towards the unification of a_1 and a_2 undergo an increase? It might be said in answer that the tendency in each half-image to unite itself with the strictly corresponding point in the other retina during a continuing change of points of retinal stimulation is not permitted to have its effect, and that indirectly, because of this, the dynamic tendency of both disparate images

to unite with each other is strengthened. And again, the intrinsic similarity of the half-images (which is the basis of the fusion tendency), is heightened by the property of "movement". The equally moved images a_1 and a_2 have a new characteristic shared in common, which binds them more closely together, and distinguishes them from the images f_1 and f_2 which are at rest.

Whatever else one may believe, the increase in displacement during objective movement may occur on the basis of an increase in the dynamic relation of the half-images, as well as on the basis of increased rapidity in eye-movements, with a constant rise in the velocity parallax. So long as there are no further experiments to preclude one or the other explanation, it would seem best to recognize the efficacy of both factors.

Supplement: The double image theories of other investigators:
It is with justification that Hering emphatically pointed out that every theory of depth perception which fails to explain the depth localization of double images must be repudiated. The problem of the double image is, in a sense, the touchstone for the validity of any theory of depth perception. When the depth perception of double images is based on the thesis that the half-images are crossed in front of the point of fixation and uncrossed behind it, this theory is bound to prove inadequate, not only because one is actually unaware of the difference, but also because after a sufficiently continued fixation, both crossed and uncrossed images can appear in the same plane. And, again, the theory that the depth of double images depends on the experience of *convergence-impulses* or -*movements* is shown to be false when it is recalled that double images, as Tschermak and Höfer have demonstrated, are pretty well localized in space during momentary illumination. Hering [11a] in his remarks on Dove's criticism of his own work says as follows:

"It has always seemed to me that the most beautiful and most striking proof for the possibility of binocular depth without eye movements is to be found in Wheatstone's observations, which show that the after-images of stereoscopic drawings also produce a tridimensional perception. One has only to take care that the after-images are produced not simultaneously but one after the other in quick succession. . . . Such an experiment excludes eye movements so to speak on principle."

[11a] Graefe's *Arch. Ophth.*, 14, I, 1868, p. 7.

Another fact which might serve as simple evidence that convergence-movements do not, themselves, influence depth, but only exert an influence that is mediated by the velocity parallax, can be demonstrated by this figure:
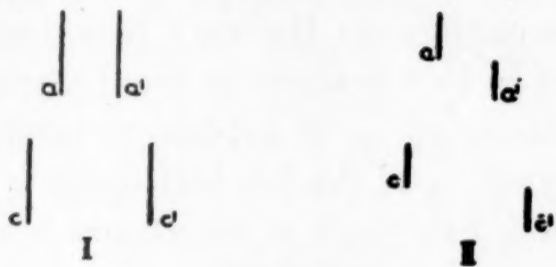
FIG. 12

If a-a^1 and c-c^1 are alternately united in Fig. 12, I, strong depth effects will appear. The half-images under such conditions are displaced, relative to the united focus-lines, and appear at a remarkable depth. When a and a^1 and c and c^1 are united in such a way that the corresponding lines are lying one exactly above the other (II), there is either very little, or no depth effect at all. The convergence-movements in I and II are the same. In II, however, there is almost no velocity parallax, the double image, at the same time, normally exhibits no displacement, and therefore appears approximately in the plane of fixation.

If cross-disparity is an indispensable factor in the perception of binocular depth in united images, it must also be a factor in the depth perception of double images. We now encounter the paradox that Hering, who did the most to ground the theory of depth perception on disparate stimuli, here discards this theory for his hypothesis of the depth values of retinal points. According to his interpretation, each point on the retina has an immutable depth value. Each point on the outer retina has a " near-value " (" Nahwert ") which increases the farther it is removed from the focus. Each point of the inner retina also has an immutable " distant-value " (" Fernwert "), which increases the more nasal the point is on the retina. This hypothesis holds good so long as it deals only with double images, both of which lie either inside or outside the fixation point (Fig. 13, I).

FIG. 13

If, on the other hand, A is brought into such a position relative to F that the left half-image a_1 lies in the outer retina, and the right half-image a_2 lies in the inner retina (Fig. 13, II), it is to to be expected, according to Hering's hypothesis, that the left half-image a_1 will be in a position in front of the fixation point, and the ri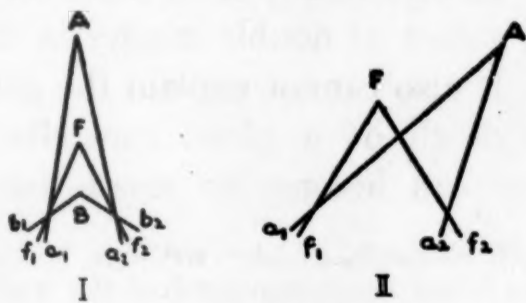ght half-image a_2 in a position behind it. And this reversion of the position of the left half-image a_1 actually occurs. In our experiments, too, there is sometimes a reversed position of the left half-image a_1 either in the case of great disparity, or when there is no right half-image a_2, or in case of a continued fixation. But—and this is the important distinction—if both half-images are given, and the disparity is not too great, then by far the most common impression is that *both* images appear *behind* the point of fixation. Hering, who was well aware of this fact, made an attempt to explain it by appending a corollary to his main hypothesis. Above all, he tried to account for this disturbing experimental fact on " empiric " grounds. Hering, therefore, has abandoned at a most significant point his theory of disparity, without being able to explain the depth of double images on the basis of his " depth-sign " hypothesis.

On the other side, Tschermak and Höfer (*l.c.*) attempted to find a solution for the problem of depth of double images in cross-disparity. The double image, according to these investigators, is in itself a unity. As a unity, the double image may be characterized by " functional disparity " as readily as the unified image. A theory depending on a gratuitous analogy is really no theory at all. In no sense is such a theory able to explain the facts revealed in our experiments. It is especially lacking in the sense that it establishes no relation between the physiological process which gives rise to depth in double images and that in unified images.[11b] Such a theory does not take into account the fact that the space values of double images in the binocular field can vary greatly. It also cannot explain the origin of the sharp differences in the depth of a given constellation. The depth can be extreme, or can become so small that there is finally

[11b] Tschermak himself, although, in later writings, taking notice of displacements in double-images is too much convinced of the truth in Hering's depth-sign hypothesis to advance a consistent dynamic theory of depth.

coincidence with the plane of fixation. Disparity can be a factor
in the explanation of depth perception only if it is understood
as a dynamic, and not an objective-static, concept. This means
that disparity must release a dynamic process, and the sign of
this dynamic process is a real displacement in the binocular field.
This seems to be possible only when disparity is conceived not
only as a relation between stimulated points, but also a relation
between stimulated and non-stimulated points of both retinas.

PART II

DISPLACEMENT AND DEPTH IN THE PANUM-CONSTELLATION

1. *The problem and the experimental set-up:*

Up to this point our experiments have shown that the binocular depth process is of much the same nature no matter whether there is a unification of both images, or not. Unification of the half-images is merely one special case of the dynamic process which leads to the phenomenon of depth. Disparity and displacement are in every case necessary conditions of this kind of depth effect.

It was shown incidentally in the experiments with the thread apparatus that a constellation which was apparently identical with the Panum-constellation was only a special instance of the binocular depth process. The Panum-pattern, as one knows, is an arrangement of figures in which the one half-image consists of two lines, and the other, of one. The Panum-phenomenon itself is the perception of two lines of different depth which are seen when the two half-images are united (Fig. 14).

To return to the experiment with the thread apparatus: If f_1 and f_2 are united, it may happen that a_1, instead of being combined with a_2, will come into a dynamic relation with f_2. It is no doubt a more favorable situation for producing the effect when f_1 and f_2 are not exactly in focus, that is, a little disparate. But this, of course, does not explain the reversed depth, often very significant, of a_1.

It can be very easily shown that the Panum-phenomenon does not actually depend, in its fully developed state, on the disparity of f_1 and f_2. Marks are placed on the upper half of the lines. These marks are equidistant, left and right. Upon the unification of f_1 and f_2, the marks appear approximately in the plane of fixation, while the half-image a_1 clearly moves forward (Fig. 15).

It is, therefore, not true, as it is so often erroneously supposed,[12] that only f_1 and f_2 have depth. The image a_1 especially moves out of the plane of fixation, for the marks which are not disparate, clearly have a different depth from the depth of a_1.

[12] *E.g.,* F. B. Hoffman, *l.c.,* 432–433.
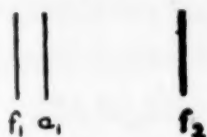
FIG. 14. Standard Panum-Pattern. Unification of f_1 and f_2
makes a_1 appear in front of f.

The depth of a_1 must be based on the fact that the half-image a_1 has a dynamic relation to the half-image f_2. This means that there is a tendency to fusion not only between f_1 and f_2, but also between f_2 and a_1. In our experiments with the thread, this fusion tendency was clearly followed by the appearance of displacement and a paradoxical depth.

Even though it has been apparently established in these experiments just discussed that depth and displacement are interde-
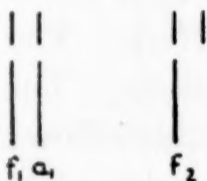
FIG. 15. Arrangement for proving depth position of a_1.

pendent in the Panum-phenomenon, there must be a further and more specialized experimental set-up in order to establish this fact beyond any doubt. The problem can be very simply demonstrated by means of a stereoscope.

Stereoscopic Pattern No. I: Objectively the line a is placed in the middle between point *1* and point f_1. b is placed in the middle between point f_1 and point s_1. *1* $f_1=f_1$ $s_1=2$ $f_2=f_2$ s_2. When f_1 and f_2 are united, the three binocular points are in the plane of fixation. In the middle between the left and the middle point a will appear; b will appear in the middle between the right point and the middle point. Stereoscopic Pattern No. II: The second pattern differs from the first in that a line c is drawn
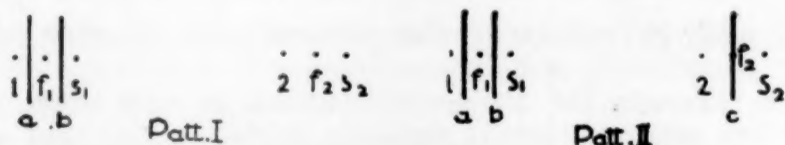
FIG. 16. Patterns demonstrating displacement in Panum-phenomenon.

through f_2. By comparison of the binocular images of patterns I and II, the influence of the half-image c on the depth and position of a and b may be investigated.

Pattern II gives a very clear depth effect.[13] The so-called Panum-phenomenon extends onto the lines a and b, that is, a appears behind, and b in front of, the plane of fixation as shown by the group of three points. A displacement can be clearly demonstrated in the Panum-phenomenon. While in the first pattern a and b appear not only in the plane of fixation, but also in the exact middle between the three points, in the second pattern there is a noticeable displacement of a and b in the direction of the middle point. The lines appear no longer in a central position between the points, but move inward in directions opposite to each other. The presence of c evokes, accordingly, the following effects: (1) a depth effect; (2) a displacement that corresponds to the depth effect. The depth effect and displacement are present in both lines. The value of such an experimental arrangement lies in the following advantages: (1) It permits the study of the dynamics of half-images, and may prove that this phenomenon leads further on to dynamic laws of general application. (2) It facilitates the study of the relation between depth effect and displacement (according to extent and direction) in the special case of the Panum-phenomenon. (3) It makes it possible to measure displacement objectively. (4) The experimental set-up takes into consideration the following valid objection: It may be that the moving together of the lines so often reported by other investigators is not a genuine binocular phenomenon, but merely the result of the different optical accommodation in binocular over against monocular observation. This possible objection cannot be overcome so long as the *monocular* image ab is compared with the *binocular* image within the Panum-pattern. In our comparison the comparison always refers to a binocular field. The relative space values of a and b are studied with reference to the presence or absence of the half-

[13] For some observers the Panum-phenomenon is very slight, or does not exist at all. The results of such a situation, so far as they have a bearing on the position of the lines a and b, will be discussed later.

image *c*. (5) Finally, it enables the investigator to decide a much-mooted question. Is the half-image *c* actually bound dynamically to *both* half-images of the other retina in the Panum-phenomenon? This reciprocal relation has been affirmed by some students of optical phenomena (Tschermak, Jaensch, and Henning), while it has been denied by others (Prandtl, Kaila).[14]

Experimental set-up:

The basis for the measurements made of the Panum-phenomenon are the two previously mentioned patterns. The measurements themselves are made possible in the thread apparatus by means of the moving signal *S* (Fig. 17). The principle of the measurements is the following: It is given that the displacement in the Panum-pattern (II) shall be related to Pattern I

FIG. 17. Binocular situations which arrive in measuring displacement.

(where *a, b* are presented without *c*). In order to accomplish this end, it is necessary that the position of the right binocular point *S* in Pattern I be determined so that *b* will lie at a central point between *S* and *F* (Situation I). After this has been done, *c* is introduced into the binocular field (Pattern II). By this change a shift of *b* towards *F* is observed (Situation II). The change in the position of *b* is registered in this way: *S* has to be moved until the line *b* is again in a central position between the two binocular points *F* and *S*. The more the binocular point *S* (in Pattern II) has to be shifted towards the left, in order to make the line *b* the middle line of *F* and *S*, the greater is the displacement in the Panum-phenomenon relative to Pattern I.

[14] Tschermak-Höfer, *l.c.*, 510.

E. Jaensch, Über die Wahrnehmung des Raumes, *Zsch. f. Psychol.*, Suppl. IV, 1909, 46 ff.

H. Henning, Das Panumsche Phänomen, *Zsch. f. Psychol.*, 70, 1905, 373.

A. Prandtl, Spezifische Tiefenauffassung der Einzelauges, *Fortschr. d. Psychol.*, IV, 1917, 257.

E. Kaila, Versuch einer empiristischen Erklärung der Tiefenlokalisation von Doppelbildern, *Zsch. f. Psychol.*, 82, 1919, 129.

The physical **arrangement** in the **thread-apparatus** **is as** fol-
lows (Fig. 18): **Two** black **threads** (*a* and *b*), which **are** visible
only to the right eye, are placed to the left against **the** white
screen that is at the **back** of the apparatus.   The middle point
f_1 (right eye) is **a** small red ball (diameter about .008 in.) which
is fastened to **a** white hair that is invisible **against the** white
screen.   To **the right** in the same plane another similar ball, red
in color, is suspended by another white thread.   This point f_2
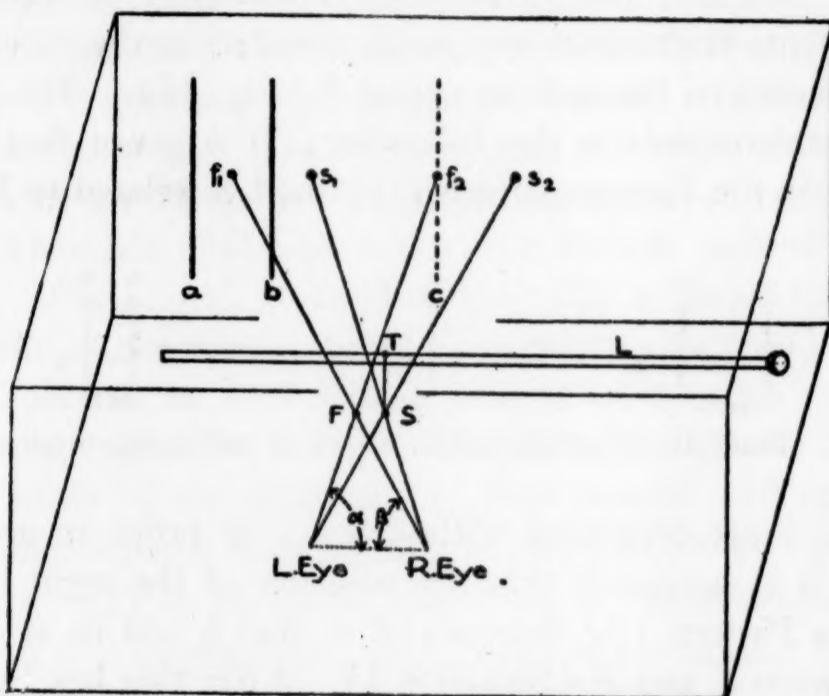
FIG. 18. Set-up for measuring displacement due to **Panum-effect.**

is visible only to the left eye.   In case Pattern II, **rather** than
Pattern I, is to be brought under observation, a black hair with
a red point f_2 is substituted for the white hair at the right side
[this line **appears** as *c* in Fig. 18].   A white invisible **hair** is
fastened to the **block** *T*, which can be moved along a horizontal
rod *L* (micrometer screw).   At a point *S* on the hair there is
attached a small black ball.   Furthermore, the following adapta-
tions have to be made: *S* must be so placed that it approaches
quite near to the binocular image of the double thread.   *F* and *S*
must be so **arranged** that they have the same objective height.
It is also necessary that *F* and *S* lie in the same apparent plane
of fixation.   This means that when *F* is focused, *S* will be seen
as a simple image and at the same distance from the observer

as F. This can be accomplished by displacing f_2, while S and f_1 are kept constant, until the image of S is seen as a simple image and at the same depth as F. This adaptation can be made very precisely. By these adaptations the previously mentioned arrangement in the stereoscope are transformed into a set-up of the thread-apparatus where measurements can be easily made. What were formerly s_1 and s_2 are now the half-images of S. It is now possible to displace S with the micrometer screw until it is distant from F to the extent that $Fb=BS$. In other words, the binocular distance of the thread b from F can be defined in such a way that a point S is placed in the plane of fixation in a position that brings the point b half way between F and S. If there is a displacement of the thread b when the thread c is introduced, then this displacement can be measured by the amount of shifting of S in Pattern II over against Pattern I.[14a]

The experiments are carried out with three O's. The objective distance between the nodal line and the fixation plane is 480–485 mm. The distance between a and b is *4, 6, 8,* or *10* mm. As we have previously noted, the distance f_1f_2 is to be adjusted so that S and F (Pattern I) are seen as single images in the same plane. All the values, empirically measured, are in terms of visual angles. The experimental results are correlated in tables. Values for two O's are given. There was no displacement in the third O. The experiment with the third O will be mentioned later when dot-patterns are discussed.

The experiment proceeded in this manner: First of all, the displacement of the thread b, and afterwards of thread a, is determined in Pattern II with respect to Pattern I. Signal S is brought to the right side of the pair of lines, and so placed that it is same distance removed from b in the binocular field as b is from F. This placing of S is carried out under both of the basic conditions of the experiment, that is, in both the presence and the absence of the third thread c. The displacement of the thread a in Pattern II with respect to Pattern I is also determined in the

[14a] The small displacements of S out of the horopter may be dismissed as negligible factors relative to the far more significant displacements to the left and right.

same way. In this latter case, S is brought to the left of the double lines and shifted until a appears in a central point between S and F.

Two double series are carried out for each distance a–b:

1. Position of S for thread b in the absence of c.
2. Position of S for thread b in the presence of c.
3. Position of S for thread a in the absence of c.
4. Position of S for thread a in the presence of c.

The values are averages taken from 20 trials:

2. Results and theoretical discussion:

TABLE VI
SHOWING AMOUNT OF DISPLACEMENT OF DOUBLE LINE IN PANUM CONSTELLATION

S.H. Distance of nodal points: 65.5 mm.
Distance of nodal line from fixation plane: 480 mm.
Visual angles of F (v. Fig. 18): $\angle a = 89° \, 44' \, 44''$; $\angle \beta = 82° \, 25' \, 30''$.

Constellation I (ab=4 mm.)
Visual angle ab, right eye=0° 22′ 5″ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 21′ 45″	0° 21′ 58″
c present	0° 14′ 0″	0° 14′ 20″
Difference	0° 7′ 45″	0° 7′ 38″

Displacement of b in terms of FS (right eye): 35.64%

(2) Space Values of Distance Fa (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 22′ 15″	0° 22′ 20″
c present	0° 13′ 25″	0° 13′ 55″
Difference	0° 8′ 50″	0° 8′ 25″

Displacement of a in terms of FS (right eye): 39.70%

S.H.

Constellation II (AB=6 mm.)
Visual angle ab, right eye=0° 31′ 46″ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 31′ 5″	0° 31′ 26″
c present	0° 22′ 5″	0° 22′ 40″
Difference	0° 9′ 0″	0° 8′ 46″

Displacement of b in terms of FS (right eye): 28.98%

(2) Space Values of Distance Fa (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 31′ 40″	0° 31′ 9″
c present	0° 20′ 35″	0° 20′ 19″
Difference	0° 11′ 5″	0° 10′ 50″

Displacement of a in terms of FS (right eye): 35.00%

S.H.

Constellation III (AB=8 mm.)
Visual angle ab, right eye=0° 41′ 5″ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 41′ 20″	0° 41′ 5″
c present	0° 31′ 5″	0° 30′ 56″
Difference	0° 10′ 15″	0ᵛ 10′ 9″

Displacement of b in terms of FS (right eye): 24.79%

(2) Space Values of Distance Fa (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 54′ 12″	0° 54′ 30″
c present	0° 42′ 59″	0° 43′ 10″
Difference	0° 11′ 13″	0° 11′ 20″

Displacement of a in terms of FS (right eye): 20.69%

S.H.

Constellation IV (AB=10 mm.)
Visual angle ab, right eye=0° 50′ 58″ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 51′ 12″	0° 51′ 20″
c present	0° 41′ 35″	0° 41′ 38″
Difference	0° 9′ 37″	0° 9′ 42″

Displacement of b in terms of FS (right eye): 18.79%

(2) Space Values of Distance Fa (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 51′ 20″	0° 51′ 22″
c present	0° 40′ 46″	0° 41′ 5″
Difference	0° 10′ 34″	0° 10′ 17″

Displacement of a in terms of FS (right eye): 20.59%

TABLE VI—*Continued*

S.J. Distance of nodal points: 63.7 mm.
Distance of nodal line from fixation plane: 483.5 mm.
Visual angles of F (v. Fig. 18): $\angle a = 88°\ 31'\ 30''$; $\angle \beta = 83°\ 54'\ 30''$.

Constellation I (AB=4 mm.)
Visual angle ab, right eye=$0°\ 24'\ 4''$ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 24' 14"	0° 23' 59"
c present	0° 17' 00"	0° 17' 5"
Difference	0° 7' 14"	0° 6' 54"

Displacement of b in terms of FS (right eye): 29.85%

(2) Space Values of Distance Fa (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 23' 35"	0° 23' 56"
c present	0° 17' 4"	0° 17' 32"
Difference	0° 6' 31"	0° 6' 24"

Displacement of a in terms of FS (right eye): 27.63%

S.J.

Constellation II (AB=6 mm.)
Visual angle ab, right eye=$0°\ 33'\ 00''$ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 32' 35"	0° 32' 59"
c present	0° 23' 25"	0° 23' 47"
Difference	0° 9' 10"	0° 9' 12"

Displacement of b in terms of FS (right eye): 28.13%

(2) Space Values of Distance Fa (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 33' 45"	0° 33' 27"
c present	0° 23' 48"	0° 23' 33"
Difference	0° 9' 57"	0° 9' 54"

Displacement of a in terms of FS (right eye): 29.48%

S.J.

Constellation III (AB=8 mm.)
Visual angle ab, right eye=$0°\ 42'\ 5''$ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 42' 40"	0° 42' 18"
c present	0° 32' 37"	0° 32' 21"
Difference	0° 10' 3"	0° 9' 57"

Displacement of b in terms of FS (right eye): 23.55%

(2) Space Values of Distance **Fa** (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 42′ 47″	0° 42′ 9″
c present	0° 35′ 28″	0° 35′ 47″
Difference	0° 7′ 19″	0° 6′ 22″

Displacement of a in terms of FS (right eye): 17.11%

S.J.

Constellation IV (AB=10 mm.)
Visual angle ab, right eye=0° 51′ 17″ (monocular)

(1) Space Values of Distance **Fb** (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 50′ 59″	0° 51′ 13″
c present	0° 40′ 47″	0° 40′ 57″
Difference	0° 10′ 12″	0° 10′ 16″

Displacement of b in terms of FS (right eye): 20.01%

(2) Space Values of Distance **FS** (binocular) in terms of FS:

	Visual angles FS	
	Right Eye	Left Eye
c lacking	0° 51′ 49″	0° 51′ 26″
c present	0° 44′ 34″	0° 44′ 17″
Difference	0° 7′ 15″	0° 7′ 9″

Displacement of a in terms of FS (right eye): 13.99%

Results:

(a) *The tables VI show that in the Panum-pattern, the line* a, *as well as the line* b, *i.e., in the presence of the third thread* c, *has a different place value than it has when the thread* c *is missing. A depth effect is present together with the displacement of both lines.* If line b appears exactly in the middle between F and S when c is absent, it will be very clearly displaced in the direction of F when the half-image c is introduced. This displacement is measured by the shift of S. S is shifted in such a way that in the new pattern, b is in the middle between F and S. Let us take the first example in the table. In the absence of c, b appears in a central position between F and S. The distance F–S is 21′ 45″ for the right eye. If the line c is introduced, b becomes a middle point between an F and an S, the distance between which is now only 14′ 0″ for the right eye. It follows that S has been shifted *35.64%* of the total distance in the direction of F. The percentage value of the shift of S in the direction of F is also the

value of the displacement of the thread *b* toward *F* in the binocular field. In the same constellation, on the other hand, there is not only a displacement of *b*, but also of *a*, in the direction of *F*. This has a value of *39.70%* measured in the right eye. The result is, therefore, that there is a diminution of the distance *a–b* in the Panum-phenomenon.

It follows from this that the appearance of a single line *c* in the one retina occasions a depth effect in *both* lines, *a* and *b*, of the other retina. It is impossible to clarify the phenomenon in any other way than by the double relation of the one line *c* to the two lines *a* and *b*.

One cannot deny, however, that the Panum-phenomenon can appear in such a manner that only one line moves out of the plane of fixation. This is often the case when the fixation point is near one of the lines. In our particular instance, the double relation is no doubt optimal when the line *c* has its corresponding point exactly in the middle between the two lines *a* and *b*, and it is because of this fact that the Panum-phenomenon develops in its most decisive form.
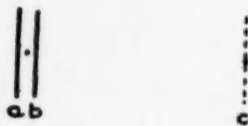
FIG. 19.   Pattern which demonstrates Panum-effect without fusion of half-images.

There are three possible theoretical explanations for this double relation. (1) Parts of the line *c* merge into the line *a*, and other parts into *b*. In the experiment with the dot-pattern it will be demonstrated that such a possibility can be realized. (2) There is a merging together of the lines *c* and *b*, while the other line *a*, because of its dynamic relation to *c*, although not absorbed, undergoes displacement, and is therefore characterized by a depth effect. It may be that there is an alternate merging of *a* and *b* with *c* if there are slight eye-movements to facilitate matters. In this event, the other line of the pair would undergo displacement as the result of a velocity parallax. Theoretically this would be the case if f_1 f_2 were not rigidly fixed. Occasional observations tend to support this hypothesis. If the line *c* is kept distinctly separate from the lines *a* and *b*, in color, shape, etc., then *c* can be unified with *a* or *b* at will. At the moment of

unification, and shortly afterwards, the other line of the pair will not be seen in the plane of the fixation point, but at a depth that is opposed to the depth of the other line. This indicates *that the Panum-phenomenon is not necessarily a merging together of the lines.* It is sufficient that the half-images of the double lines come into dynamic relation with the single line. (3) The third possibility is, that the line *c* does not merge either with *a* or *b*. It can be shown by the use of the pattern that has just been given in Fig. 19 that the Panum-phenomenon, *i.e.*, depth and displacement, is present, even when *c* stands clearly between *a* and *b*. All that is necessary to bring this about is the comparatively inaccurate fixation of *F*. Slight eye-movements will support the underlying effect.—It seems, then, that all three possibilities can become realized.

FIG. 20. Displacement in the right eye.

(*b*) *The direction of displacement determines the direction of the depth effect in the Panum-phenomenon exactly as it did in the experiments with binocular double images. A nasal displacement causes a depth movement forward, and a temporal displacement, a movement backward.* Because of this the line *a* will appear in front of the plane of fixation, and the line *b* behind.

(*c*) *In general the clarity and strength of the depth effect is dependent on the amount of displacement.* On an average the tables show that (from a certain distance on) the displacement becomes relatively smaller as the distance *a–b* increases. Jaensch's experiments [15] with the Panum-phenomenon led him to believe, and our own results compel us to agree with his views, that the depth effect, after a certain distance *a–b* is reached, decreases concurrently with the further increase of the distance *a–b* until a maximum is reached, at which point it vanishes. We may therefore assume that, ceteris paribus, the strength of displace-

[15] *l.c.*, pp. 46, 559.

ment is a phenomenon which runs parallel to the strength of the depth effect.[15a]

The relation between displacement and depth effect can be directly illustrated by the behavior of the *O C*. In this experiment *O C saw no displacement,* and we have therefore left a blank for his values. Moreover, *it must be noted that, for him, there was no Panum-effect at all.* It is well known that there are individuals who do not see the Panum-phenomenon in its usual form. Proceeding on the assumption that the conventional Panum-pattern did not furnish sufficient stimulus to bring into play a dynamic relation between *c* and *a–b*, we sought for a pattern which would intensify the stimulus. It was this premise that led us to construct the " dot-pattern " which serves as the basic form in another series of experiments.

Fig. 21. Typical dot-pattern.

3. *Dot-pattern with respect to the full-line pattern:*

The dot-pattern is so constructed that the single line can be split into two pieces, one of which is related to the right side of the double line, and the other to the left side. As far as the Panum-phenomenon is concerned, this pattern affords the means of giving a precise answer to the problem of the double relation of the single line to each part of the double line. Fig. 21 illustrates one of the variations of the dot-patterns used in the experiments.

If the binocular unification is complete, there will be seen in the stereoscope two vertical series of 3, resp. 4 dots, and one of the series clearly stands in front of the other. In order to compare the depth effect in the dot configuration with the normal Panum-pattern, ten subjects were tested. The dot-patterns and full-line patterns which were compared were of equal length and distance apart. Both patterns were presented simultaneously, and also

[15a] In reality the relations are more complicated. Discussion later: Part **V**.

in succession. The observers were asked to pass judgment on the depth impressions which these patterns produced. The results of the observations are brought together in the following table VII. The reactions of the observers are divided into four groups: " very decisive depth impression ", " slight depth impression ", " occasional depth impression ", and " no depth impression ". After the O was adapted to these figures, each pair was given a series of 10 trials, each of which lasted 20 seconds. In all five combinations of dot-patterns were used.

According to this table, the dot-pattern shows a higher percentage of cases where the observers have a very definite perception of depth. Of 10 Os, three were unable to see depth in an ordinary full-line pattern. On the other hand, all the Os saw

TABLE VII

PERCENTAGE DISTRIBUTION OF THE DEPTH REACTION (10 O's, 500 trials)
FULL-LINE PATTERN vs. DOT-PATTERN

	Very decisive	Slight	Occasional	No depth
Full-line pattern	43%	18%	6%	33%
Dot-pattern	85%	10%	5%	—

depth when the dot-pattern was used. When both patterns were introduced simultaneously, all Os concurred in the opinion that there was more depth effect in the dot-pattern than in the full-line pattern.

Bringing all these results together, we see that the *depth effect is strengthened when the dot-pattern is used instead of the full-line pattern.*

The results of the stereoscopic experiments are now subjected to an accurate check-up by the use of the thread apparatus. In order to check up on the relation between the depth effect and displacement, it was necessary to substitute the dot-pattern for the full-line pattern previously used. The half-image for the right eye is on the left, and the half-image for the left eye is on the right.

The threads to which were fastened the dots in the form of small black balls, were light-grey. In all other respects the arrangement was the same as it was for the full-line pattern.

In order to measure the displacement, the same method of shifting the signal *S* was used.

TABLE VIII

SHOWING THE AMOUNT OF DISPLACEMENT. OF THE DOTTED LINES a AND b
IN PANUM CONSTELLATION (Subject C)

Constellation I (AB=4 mm.)
Visual angle ab, right eye=0° 20′ 5″ (monocular)

(1) Space Values of Distance Fb (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 19′ 45″	0° 19′ 52″
c present	0° 10′ 32″	0° 10′ 40″
Difference	0° 9′ 13″	0° 9′ 12″

Displacement of b in terms of FS (right eye): 46.66%

(2) Space Values of Distance Fa (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 20′ 35″	0° 20′ 58″
c present	0° 12′ 33″	0° 12′ 42″
Difference	0° 8′ 2″	0° 8′ 16″

Displacement of a in terms of FS (right eye): 39.03%

Constellation II (AB=6 mm.)
Visual angle ab, right eye=0° 30′ 5″

(1) Space Values of Distance Fb (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 29′58″	0° 30′ 15″
c present	0° 23′ 14″	0° 23′ 0″
Difference	0° 6′ 44″	0° 7′ 15″

Displacement of b in terms of FS (right eye): 22.48%

(2) Space Values of Distance Fa (binocular) in terms of FS:

| | Visual angles FS | |
	Right Eye	Left Eye
c lacking	0° 30′ 0″	0° 30′ 45″
c present	0° 26′ 5″	0° 26′ 33″
Difference	0° 3′ 55″	0° 4′ 12″

Displacement of a in terms of FS (right eye): 13.06%

The experiments with *O C* were of especial importance. This observer saw absolutely *no depth* in the *simple Panum-pattern* when the thread apparatus was used. Neither did he see any depth effect when the Panum-pattern was presented by means of the stereoscope. And, in keeping with this situation, the same observer saw *no displacement in the ordinary Panum-pattern*.

In contrast to this behavior, the observer *C* saw a *decided depth effect when the dot-pattern was brought into play.* This held true both when the stereoscope and the thread apparatus were used. In all cases the observer was able to see the effect only at a small distance between *a* and *b* (4–6 mm.). It will be interesting to note the displacement when the observer does see a depth effect. The results are set down in table VIII.

TABLE IX

SHOWING AMOUNT OF DISPLACEMENT IN DOT-LINE PATTERN VS. FULL-LINE PATTERN

Amount of Displacement in Full-Line Pattern

		S.H.	S.J.	S.C.
4 mm.	a	39.70%	27.63%	0%
	b	35.64%	29.85%	0%
6 mm.	a	35.00%	29.48%	0%
	b	28.98%	28.13%	0%
8 mm.	a	20.69%	17.11%	0%
	b	24.79%	23.55%	0%
10 mm.	a	20.59%	13.99%	0%
	b	18.79%	20.01%	0%

Amount of Displacement in Dot-Line Pattern

		S.H.	S.J.	S.C.
4 mm.	a	40.15%	39.58%	39.03%
	b	40.35%	43.12%	46.66%
6 mm.	a	38.25%	34.14%	13.06%
	b	30.58%	36.19%	22.48%
8 mm.	a	27.75%	28.12%	0%
	b	25.80%	28.16%	0%
10 mm.	a	20.65%	20.14%	0%
	b	20.15%	22.21%	0%

At an objective distance of *a–b=8 mm.* there was neither depth effect, nor any appreciable displacement.

These results illustrate with particular clarity the close relation between displacement and depth effect in the Panum-phenomenon. (1) *When the depth effect is missing, there is no displacement.* This is demonstrated in the experiment with the full-line pattern. (2) *When the depth effect is present, then there is an appreciable displacement of both lines towards the middle.* This will occur when the *dot-pattern is substituted for the full-line pattern.* In such case, the values of the results are not different from the results gotten from the observations of the other *O*'s.

It is of further interest to note how the other O's react to both the patterns. In the table IX on p. 49, the results of the observations of the three Os are correlated. The values indicate the per cent of displacement in both Panum-patterns. The results for the dot-pattern and for the full-line pattern are kept separate.

All the experiments reveal a decided increase of displacement when the dot-pattern is substituted for the full-line pattern. The increase chanced to have a higher value for the O $J.$, who, in the experiment with the full-line pattern saw a smaller displacement than the O $H.$ The greatest increase is, naturally, in the case of O $C.$, who, when the dot-pattern is used, sees a distinct displacement (at 4–6 mm.), while he sees none at all in the full-line pattern.

Summarizing all this, it may be said that *observations made both on the thread-apparatus and the stereoscope demonstrate that the dot-pattern provides the stimulus for a greater depth effect than does the full-line pattern. Parallel with this, it is also shown that the dot-pattern evokes a greater displacement than the full-line pattern.*

The origin of the superiority of the dot-pattern as a stimulus with reference to depth effect and displacement is to be found in the difference between the configurations of the two. The *dynamic relation between the single and the double line is intrinsically more intensive in the case of the dot-pattern than it is in the case of the full-line pattern.* By the use of the dot-pattern, the observer is compelled unconditionally to identify in simultaneity the single line with both of the double lines. This means that the dynamic relation works precisely in two opposed directions. Since displacement depends essentially on this fusion tendency, and since the depth effect parallels the displacement, the striking effects noted in the dot-pattern are easily explained: the strongest displacement and the strongest depth effect occur in the Panum-phenomenon when the dynamic relation of the single line to the double is working precisely in two opposed directions.

PART III

Depth and Displacement in Strobostereoscopic Vision

1. *The problem and experimental set-up:*

The strobostereoscope, as the name implies, is a combination of stereoscope and stroboscope.   By means of this apparatus it

Short Description of Fig. 22 (Strobostereoscope)[15b]

The pictures I and II, held in the frames A_1 and A_2, after receiving illumination from the lamps L, are projected through the lenses M, N and O, P, respectively, and are reflected from the mirrors B and C to the milk-glass S. The projections are interrupted by episcotister disks D and E, respectively. The disks are operated by means of motor Q and gear R.   The speed of rotation is varied by a rheostat T, to which a scale is attached.   The observer looks through the curved prisms U_1 U_2 at the milk-glass S where the images appear.
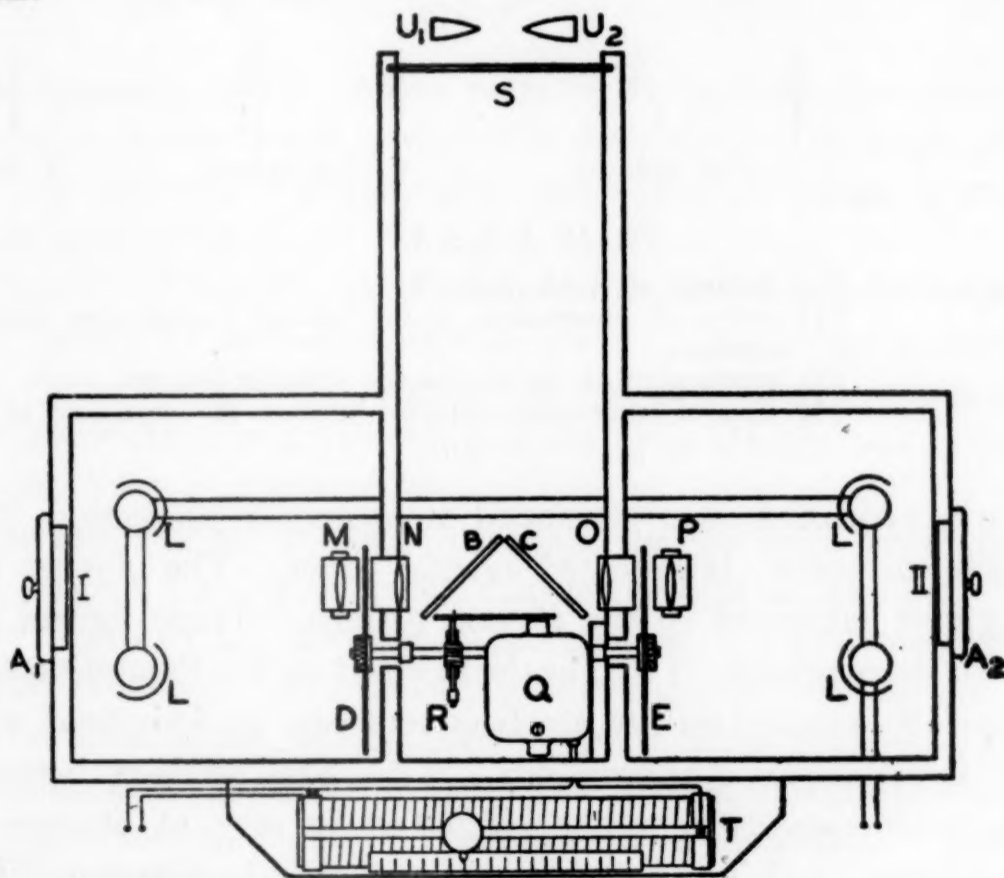

Fig. 22.   Strobostereoscope.

[15b] The stroboscope has been designed by Dr. B. D. Thuma and could easily be adapted for the stereoscopic procedure.

is possible to project stereoscopic images in such a way that the half-images *appear one after the other*. The right hand image can precede the left, and vice versa, depending on the effect that is wanted. The speed of the succession and the duration of the projection can be varied. The value of a strobostereoscopic arrangement lies in the fact that the half-images, when temporally separated, can be subjected to individual analysis in order to determine what properties they must have if they are to give rise to a stereoscopic effect.

Types of figures used in the strobostereoscopic experiment reproduced in Fig. 23, 1–5.

Left   Right

1. Basic pattern

2. Dot pattern   3. Stair pattern   4. Bow pattern   5. Zig-zag pattern
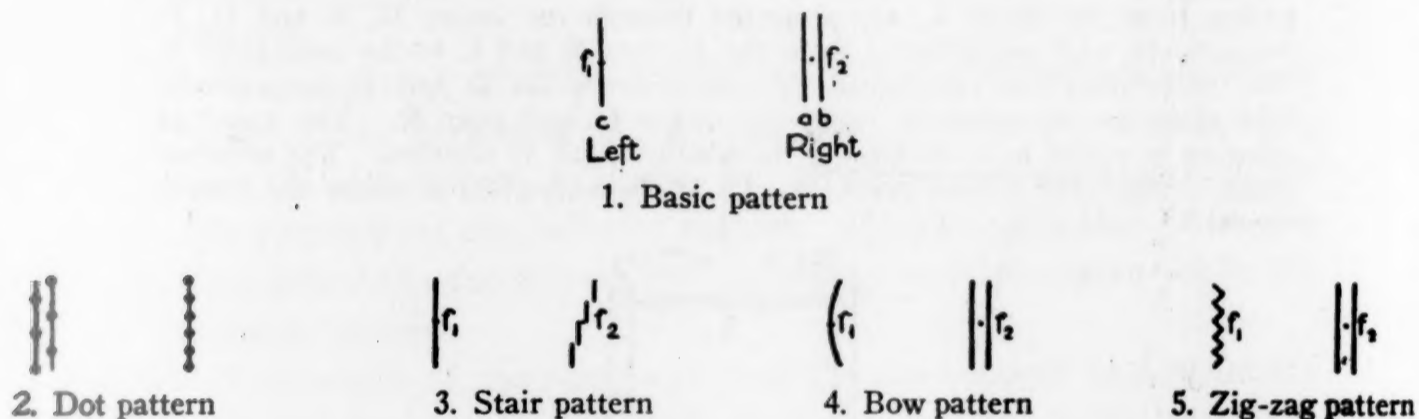
Fig. 23—1, 2, 3, 4, 5

The variations concern (1) distance ab (vid. Fig. 23, 1).
                        (2) order of succession: $c \rightarrow ab$, $ab \rightarrow c$ ($\rightarrow$ indicates order of succession).
                        (3) appearance of ab or c in the right or left eye.
                        (4) time of succession = interval between the exposures ab and c.

The presentation is a continued stroboscopic projection, that is, each succession is repeated several times. The *figures* are throughout variations of the *Panum-pattern*. These figures are used for three reasons: (1) The depth effect of the Panum-pattern is especially marked in the strobostereoscope as compared with other stereoscopic configurations. (2) The relation between stroboscopic movement and depth effect is easy to observe in these figures. (3) The half-images are distinctly different. The share which each half-image has in the total depth effect is therefore clearly discernible.

2. Experiments with the basic pattern:

(A) General results

Strobostereoscopic experiments reveal a series of characteristic phases, the appearance of which is conditioned by two factors: (1) The speed at which one half-image follows the other. (2) The distance separating the double lines of the Panum-pattern.

The phases with respect to speed of succession (*succession* |→||, or ||←|):

Three principal phases and a preliminary phase can be readily distinguished. These different stages may be called here the preliminary phase, and phases I, II, and III. The succession is $c \rightarrow ab$.
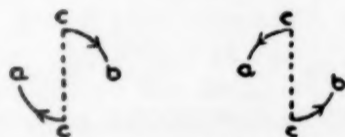
FIG. 24. "Revolving-door" movement (Phase I).

Preliminary phase: When there is a relatively low speed of succession, a movement is visible in the plane. The single line c (of the left eye, for example) parts into two lines a and b (right eye).

Phase I: When the speed of succession is increased, the movement occurs in three-dimensional space. This stage is particularly characterized by a motion of the half-images which suggests the motion of a revolving door. Fig. 24 presents a cross-sectional view of the motion.

The line c is, so to speak, perceived as two lines which cover each other. The "c in front" turns towards a; and the "c in back", towards b. Because of this motion, c is gradually transformed into a–b. At the end of the motion the line a–b lies more or less in the frontal plane. Quite often there is a complete rotation. In this first stage, *all movements are characteristically reversible*. The "revolving door movement" can be seen reversed as illustrated in Fig. 24. In case there is a rotating motion, it can proceed from left to right, or from right to left.

Phase II: If the speed of succession is increased still further,

the "revolving door movement" is no longer typical. A more or less straight three-dimensional movement, represented in cross-section by Fig. 25, now becomes typical. The second stage differs in other ways from the first. (1) The path of movement is shortened. It no longer has its beginning in c, and its end in a or b, but takes a course somewhere between them. The single line c, therefore, is no longer visible. Only two lines are to be seen. These move away from each other in opposed directions. The greater the speed of succession, the shorter the total movement. (2) Because of this, it follows that the one line will move backward in the front field, and the other in the field at the rear (vid. Fig. 25, A).

Fig. 25. Apparent three-dimensional movements of Phase II.

If the projection at this rate of speed is continued, however, another and different movement subsequently may appear. (See Fig. 25, B.) It appears more as if the two lines are in a plane which is diagonal with respect to the frontal parallel plane, and as if the lines are moving in opposite directions. (3) Whatever the movement, there is a *predominance of one particular kind of movement* as far as its position in the three-dimensional space is concerned. In the first stage, a will be seen moving in the field nearer to the observer, and b in the field farther away from him. Again, b will come forward, and a will retreat to the field formerly occupied by b. In the second phase there is no such reversal of the field of motion. One of the double lines is moving in front of the other and continues moving this way, meanwhile the other line is moving in the back field: the direction of the motion is no longer reversible. *Predominance of one direction of movement, that is, predominance of cases of irreversible motion, are characteristic of the second phase.* If we investigate to find out which kind of motion is irreversible, we find that it corresponds in every case with a stereoscopic effect where both images appear simultaneously (Fig. 14). In the case of

|→||, the left line of the double line is in the frontal field; and in the case of ||←|, the reverse is true. We shall denote the second stage as the strobostereoscopic optimal phase.

Phase III: If the speed of succession is increased sufficiently (providing *a* and *b* are not too far apart), the movement, as it progressively shortens, will flicker and jerk. The stereoscopic effect in this flickering stage is usually somewhat less sharp than in case the motion is more pronounced. The depth situation is not reversible, and is in correspondence with the stereoscopic impression which the images would make if simultaneously exposed.

If the images are given in the succession |←||, or ||→|,[15c] there is no change in the general results, with the exception of one *O*, so far as the phases are concerned. Depending on the speed of succession, the stages follow one another in this more or less typical manner: Preliminary phase: a merging together of the two lines; movement in one plane. Phase I: a "revolving door movement"; reversibility of the depth movement. Phase II: a diagonal movement of the lines in opposite directions, with a gradual decrease in the amplitude of the motion; predominance of a "stereoscopically correct" depth position which is in keeping with the phenomenon of irreversibility. Phase III: flickering, irreversibility of the depth position. . . . One observer offers exceptions to what we have stated is characteristic of the series of stages. At a sufficiently high speed of succession, the double lines, for him, vanish completely. This observer sees only one line moving backward and forward, with the extent of its movement steadily decreasing. In such a case nothing definite can be said about how far the depth movement identifies itself with a stereoscopic effect. It may also be remarked that other *O*'s occasionally see only a single line moving backwards and forwards in place of the double line.

The phases with respect to distance a–b:

The phases, besides their dependence on the speed of succession, are determined by the distance separating *a* and *b*. The following facts hold true for all cases: (1) As the distance separating the double lines is increased, the phases are shifted in the direction of higher speed of succession. This means that the greater the distance between *a* and *b*, the higher the speed must be in order to occasion the changes from the preliminary stage up through stages I, II, and III. (2) If the distance between *a* and *b* reaches a certain maximum (a value which varies for different *O*s) it becomes impossible to arrive completely at phase III. Instead of the phenomena of the third

[15c] *E.g.*, first the double, afterwards the single line.

stage, there are irregular impressions. Either two lines **without** depth movement **are** visible, or the movement is that of **the second** stage, or three lines, *i.e., c* between *a* and *b*, are seen.

(B) *Quantitative results:*

The measurements are limited to those successions **in which** the single line appears first, and is then followed by the **double** line. Since it apparently makes little or no difference **which** half-image is given to the right or left eye, we have **evaluated** the two possible variations in presentation together.

Explanation of table X and of diagram Fig. 26:

The table gives the results (in per cents) of the **relation** between the speed of succession and the phases for five **different** distances separating *a* and *b* as seen by three observers. **The first** column in table I refers to the temporal succession (in σ) of **the** two images. The second column refers to the duration of **one** complete revolution of the stroboscope disk (equals the **time** between two successive exposures of picture, 1, resp. picture 2). This duration is measured in seconds. The per cents in the succeeding columns refer to those trials (among 20 trials **for** each speed of succession) which were characteristic of phases I, II, and III. Reversible depth movement is characteristic **of** phase I, and a predominance of stereoscopic depth movement **is** characteristic of phase II. 20% " cases of phase II " **indicates** that, in four cases out of twenty, the observers saw a **stereoscopic** depth movement at a speed of succession which made it **difficult**, or quite impossible, to reverse. It is characteristic of **phase III** that there is a flickering together with a more or **less clearly** defined path. Each per cent column is to be read from **the top** down in this way: Every column begins with a record of **a** number of judgments which are applicable to phase I. **It shall** not be considered that phase I has been reached until at **least** 60% or more of the judgments characteristic of phase I **are** made. (The full line between the numbers indicates the **limit**.) The percentile values refer to the judgments made relative **to** phase II underneath the dotted line which is marked by **the** number " II ". The dotted line placed aside the II does **not**

indicate that the second phase has been reached. The second phase is reached only when 60% or more of the observers' judgments confirm it. This limit is also marked off by a full line. After this there is another dotted line with the number III, which indicates that the percentages refer to judgments made by the observers relative to the third stage. The full line with the notation III means that here is the limit between phases II and III (60% " III-judgments "). For example : The first percentage column reveals that the first phase begins before 700σ and lasts beyond 250σ. The second phase begins before 225σ and lasts beyond 150σ. The third phase begins before 125σ. In order to save space this table was made to contain the results of only three Os.

The next *diagram,* Fig. 26, on the other hand, refers to the observations of all five Os. In it are represented the principal phases I, II, and III for five different distances of a–b of the Panum-pattern. From the theoretical standpoint it is especially important to take note of the inception of phase II, *i.e.,* that stage in which reversibility of the depth effect is replaced by irreversibliity.

In spite of the great individual differences among the Os, it is quite possible to derive from the table X and diagram Fig. 26 that law governing the interdependence of the distance a–b and the speed of succession which we have already mentioned. It is especially notable that the change from reversibility to irreversibility occurs proportionally later when the distance between the lines a and b has increased. Under the given conditions, the distance 8.5 mm. appears to be the extreme limit at which the flickering phase III can be reached.

The phases and the shortening effect (displacement):

All observers agree that both members of the double line are seen increasingly closer together when there is an increase in the speed of succession, an effect which has already been measured in the Panum-phenomenon by means of the thread apparatus. It is a pertinent question whether this effect could not be demonstrated objectively in the strobostereoscopic experiments. In all

TABLE X

SHOWING THE RELATION BETWEEN THE THREE STAGES AND THE SPEED OF SUCCESSION

Succ. σ	Time of Rotation Sec.	S₁ 2.5 mm %	S₁ 4 mm %	S₁ 5.5 mm %	S₁ 7 mm %	S₁ 8.5 mm %	S₂ 2.5 mm %	S₂ 4 mm %	S₂ 5.5 mm %	S₂ 7 mm %	S₂ 8.5 mm %	S₃ 2.5 mm %	S₃ 4 mm %	S₃ 5.5 mm %	S₃ 7 mm %	S₃ 8.5 mm %
750	3.0	50	50	40	—	—	40̲I̲	—	15	—	—	—	—	—	—	—
725	2.9	50̲I̲/75	55̲I̲/60	30	—	—	90	25	35	—	—	—	—	—	—	—
700	2.8	95	85	35̲I̲/85	—	—	100	50̲I̲/85	50̲I̲/75	—	—	—	—	—	—	—
675	2.7	100	90	95	—	—	"	100	90	10	—	—	—	—	—	—
650	2.6	"	100	100	20̲I̲/75	—	"	"	100	45	10	—	—	—	—	—
625	2.5	"	"	"	"	15	"	"	"	40̲I̲/85	45	—	—	—	—	—
600	2.4	"	"	"	90	20̲I̲/75	"	"	"	75	30̲I̲/90	—	—	—	—	—
575	2.3	"	"	"	100	"	"	"	"	100	"	—	—	—	—	—
550	2.2	"	"	"	"	100	30̲II̲	"	"	"	100	—	—	—	—	—
525	2.1	"	"	"	"	"	30̲II̲/66	"	"	"	"	—	—	—	—	—
500	2.0	"	"	"	"	"	100	35̲II̲	"	"	"	—	—	—	—	—
475	1.9	"	"	"	"	"	"	—II	"	"	"	35	—	—	—	—
450	1.8	"	"	"	"	"	"	"	"	"	"	50̲I̲/85	20	—	—	—
425	1.7	"	"	"	"	"	"	"	"	"	"	85̲II̲ / —I	40̲I̲	—	—	—

400	375	350	325	300	275	250	225	200	175	150	125	100	75	50	25
—	—	—	—	5	55/70 I	75	100	100 II	25	35 II	65 III	25 III	100	100	
—	—	—	—	35	25/65	95	100	95	100 II	40 II	40 III	75	95	100	
—	—	35 I	60	60	75	100	"	30 II	20	45 II	75 III	55 III	80	100	"
85 II	20/75 II	95	80	100	"	"	"	30 III	45/90 III	100	"	"	"		
10	50/90 II	100	80	100	"	"	"	25/65 III	100	"	"	"	"		
"	"	"	"	"	"	"	"	"	20 II	65 III	20/75 III	100	"		
"	"	"	"	"	"	"	"	"	30/95 II	20/80 III	100	"			
"	"	"	"	"	10/60 II	100	"	"	20/80 III	"	"	"	"		
65	85	100	"	"	"	"	"	10 III	35/85 III	"	"	"	"	"	
"	"	"	20 III	(60)	40	50/70 III	90	100	"	"	"	"	"	"	
"	"	"	"	"	"	"	25 II	20	35/80 II,III	20/65 II,III	95	100			
"	"	"	"	"	15 II	15	55/70 II	100 III	25	45/95 II	100	"	"		
"	"	"	"	"	25 II	(60)	40	80 II	10	40 III	95	100	"	"	
"	"	"	"	10/75 II	100	10 III	40/80 III	100	"	"	"				
"	"	"	"	25/85 II	100 III	20	35/90 III	100	"	"	"				

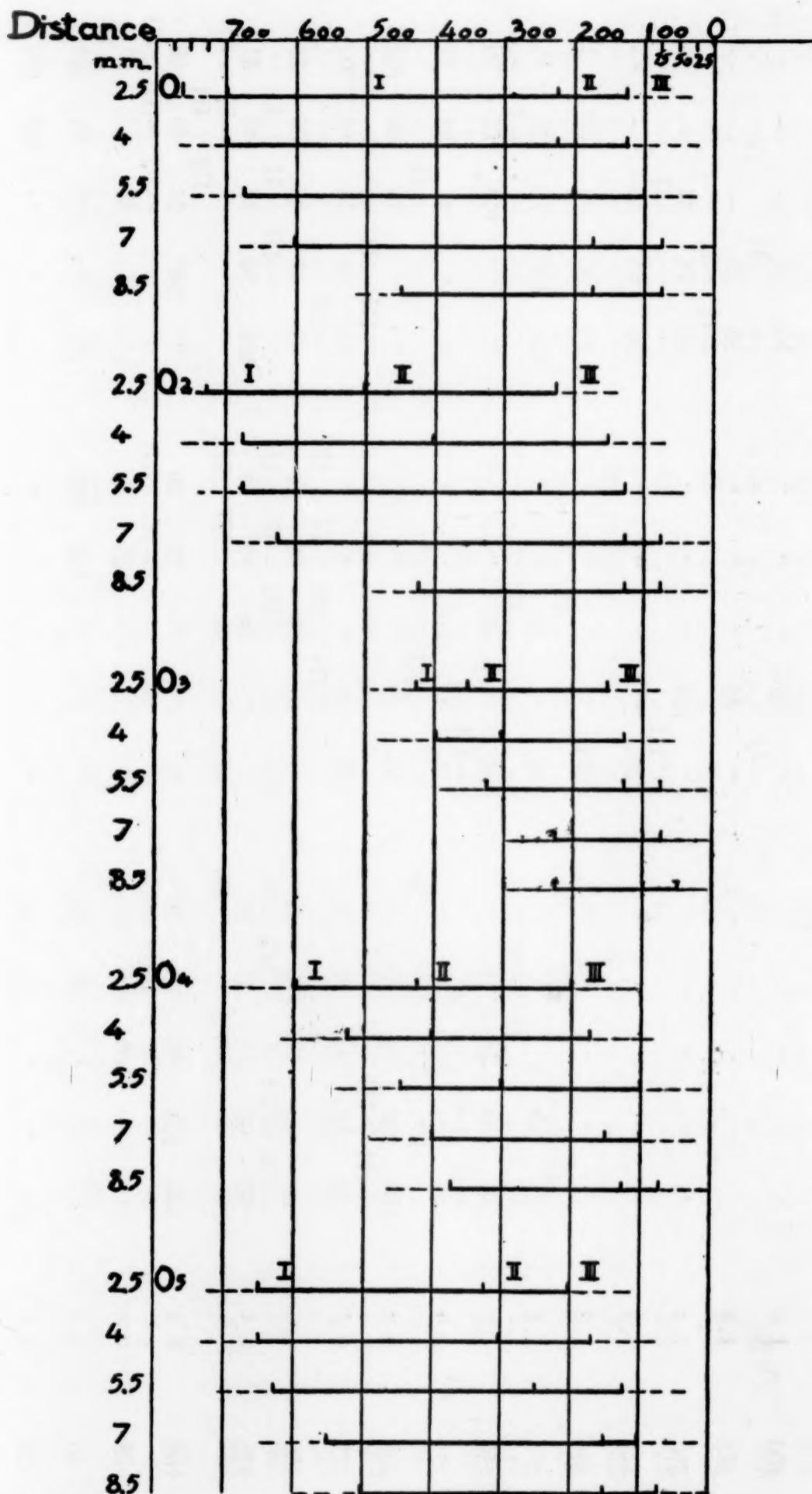| 1.6 | 1.5 | 1.4 | 1.3 | 1.2 | 1.1 | 1.0 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |

Fig. 26.   Diagram indicating 3 stages (σ) in relation to 5 distances
(2.5, 4, 5.5, 7, 8.5 mm.) 5 O's.

events, it would require a complicated apparatus actually to measure the effect. For this reason we have let it suffice to demonstrate it qualitatively. The pattern used is, in principle, the same as that used in the thread apparatus (Fig. 27).

The points *1* and *3* are the focal points, and *2* and *4* are points which are equidistant from the focus. These points can be seen continuously on the projection glass. Therefore, upon the unification of points *1* and *3*, and of *2* and *4*, in the stereoscope, two points are seen continuously in the plane of the milk-glass. The distance of the line *b* from *3* and *4* is so chosen that it lies exactly half way between them. If there is a marked shortening of the distance between *a* and *b* during the stroboscopic exposure, this shortening must be reflected in the phenomenon that the movement no longer ends in the middle between the two points, but over farther towards the inside, that is, nearer to the center.
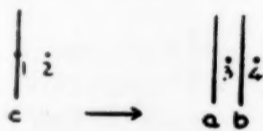
FIG. 27. Pattern for demonstration of the strobostereoscopic shortening-effect.

In the following table XI are recorded the significant average results reported by 5 *O*s for the distance 4 mm.

Upon examination the tables will be found to reveal these facts: With the exception of *O 3*, that is, the observer who, throughout all the experiments saw but a very slight depth effect, all the *O*s saw that the distance separating the double line decreased after a certain speed of succession was attained. This decrease begins in the higher speeds of succession of phase II; and the maximum decrease is reached in phase III. None of the observers noted any shortening in stage I. In order to find out whether the shortening was no more than a simple stroboscopic effect, an analogous monocular experiment was carried out. A normal (non-stereoscopic) stroboscopic arrangement was made. The images, which are presented in a succession, are those of Fig. 26, with the difference that the single line *c* now appears objectively in the middle between *a* and *b*. A shortening of the

double line *a–b* could not be observed in the field of the normal stroboscopic optimum, neither in the succession *c→a–b,* nor in the succession *a–b→c.* This indicates that the shortening cannot be based on a simple stroboscopic effect.

TABLE XI

Demonstrating the Relation Between Speed and Shortening-Effect

	Stage	Succession (σ)	Report
O_1	I	700	No shortening
	I	225	" "
	II	175	Slight shortening
	II	150	Shortening very distinct
	II	125	Increase of shortening with time of succession
	⋮	⋮	⋮
O_2	I	675	No shortening
	I	400	" "
	II	225	Shortening slight
	II	200	" "
	II	175	Line b displaced to about ⅓ of original distance towards center
	II	150	" " " " " "
	III	125	Displacement to exactly a third
	III	100	Displacement to about a fourth of original distance towards center

O_3: Very slight effect

	Stage	Succession (σ)	Report
O_4	I	525	No shortening
	I	400	" "
	II	250	Slight effect
	II	200	Shortening increases
	II	175	Displacement to a third of original distance to the center
	III	150	Lines very near the center

O_5 Reactions similar to O_2

(C) *Theoretical discussion:*

(1) *Binocular effect vs. alternate-ocular effect:*

Two very remarkable facts are revealed in these experiments. First, the depth phenomenon appears in two diverse forms. There is a very impressive depth movement, which is reversible in the slow succession. At higher speeds of succession there is a depth movement that is irreversible. The reversible movement shows depth characteristics which might correspond to those of a true stereoscopic situation; on the other hand, however, an effect which is directly opposed to the stereoscopic situation can be evoked with equal ease. *Second, a true stereoscopic depth is*

*attained not only when there is a simultaneous or quasi-simul-
taneous presentation of both half-images, but even at that stage
where there is a decided succession in the presentation of the
half-images.*

As we have repeatedly remarked, phase I is characterized by a
reversible depth effect. It has been firmly established that dis-
parity plays no rôle here. What is the origin of the depth effect?
If the following images (Fig. 28) are seen in monocular succes-
sion in a simple stroboscope (the points *f* cover each other
objectively), a simple plane movement will appear in a slow
succession. The single line splits in two.

Three-dimensional movements are very common at higher
speeds of succession. There is often a " revolving door move-
ment ", or a complete rotation, similar to that observed in the
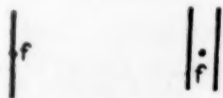strobostereoscope. This movement is always *reversible;* in other

FIG. 28. Two pictures used in a simple stroboscopic set-up.

words, *phase I of the strobostereoscopic motion does not differ
from such a monocular movement that has depth.* This depth
effect of phase I has nothing in common with the depth that is
dependent on disparity.

Movement in phase I is analogous in principle to a monocular
depth movement (or a binocular depth movement which is not
based on disparity). This kind of depth movement is governed
by the normal stroboscopic laws of movement. The difference
lies merely in the fact that, under normal stroboscopic conditions,
the stimulus has its effect either in the one eye, or in both eyes
at once, while in the situation characteristic of phase I, the
stimuli work alternately in the one eye, and then in the other.

If, for example, two lines lying in different parts of the visual
field are offered one after the other for observation, it is of no
consequence whether these lines appear both to one eye, or each
line to one of both eyes. In either case the observer sees a strobo-
scopic movement from one part of the visual field to the other.
Such a depth movement, which has the same value as a monocular

motion, and which is shared *alternately* by both eyes, we shall
term, for lack of a better expression, an "*alternative-ocular*"
depth movement. *Alternate-ocular depth movements in phase I
are throughout the same as monocular depth movements.* They
are ambivalent, and for this reason do not correspond to the depth
which is the result of binocular disparity. The depth movement
in phase II differs basically from its counterpart in phase I.
This second kind of depth corresponds to the depth situation as
occasioned by *simultaneous-binocular* disparity. This kind of
depth may be termed a "*binocular-disparate*" depth movement,
or, more simply, "*binocular*" depth movement. The difficulty
in explaining such a stroboscopic, binocular depth movement
rests in the fact that apparently the disparate points in both
eyes are not stimulated simultaneously, but, at least superficially
observed, receive an alternate-ocular stimulation. In order to
surmount this difficulty, it might be assumed that the stimuli
appear objectively in succession, but are physiologically simul-
taneous. This hypothesis is made virtually untenable when it
is recalled that the movement sometimes occurs at a rate of suc-
cession as slow as 500σ, at which point it is hard to believe in
the possibility of physiological simultaneity. Again, the very
fact that *movement* is present in the situation would logically
contradict the possibility of simultaneity. In the physiological
sense, simultaneity can occur only when movement ceases, *i.e.,* in
phase III. Since phase III, however, is different from phase II,
it is not possible to apply any theory which depends on the simul-
taneity of the physiological process. Another explanation must
be sought for. Any explanation must have the premise that
there is an *actual succession* of half-images. In this case it is
quite feasible to explain the depth process on the basis of dis-
parity, even when the images definitely appear one after the other.
As one may recall, the experiments with half-images suggested
that a half-image may stand in disparate relation to a point in
the other retina that has received no stimulus. The experiments
with fragmentary images—which will be reported in the next
chapter—lend support to this hypothesis. As we shall demon-
strate there, it is possible to attain a real stereoscopic depth even

when the one half-image has no related points that have been stimulated in the other retina. If b is fixed (vid. Fig. 29), and an attempt is made to see a_1-a_2 as a connected line, then a_1-a_2 will appear before b. This part-image-stereoscopy indicates that the disparate points in opposite retinas need not both be stimulated in order to occasion depth. It suffices that the one half-image be visible and—as a consequence of the special configuration—in relation with a disparate point of the other retina that did not receive a stimulus. In such a case, a binocular process develops which binds together stimulated and non-stimulated points in the two retinas.

In a certain sense, such experiments with fragmentary images are analogous to strobostereoscopic experiments. It should not
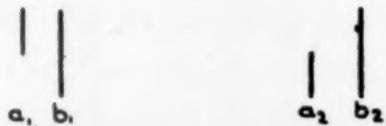
$$| \quad | \qquad\qquad | \quad |$$

a, b,　　　　　a₂ b₂

Fɪɢ. 29.　Fragmentary stereoscopic picture.

make any particular difference whether the fragmentary character of the picture refers to a spatial condition, as in the case of fragmentary images, or to a temporal condition, as in the case of the strobostereoscopic experiments. The difference is merely that the images supplement each other temporally, instead of spatially. Each visible half-image, when it is conditioned by the stroboscopic arrangement, is related to an invisible, disparate point in the other eye. *The objective alternation of the visible monocular images corresponds to a real, continuous binocular process.* The visibility of the images changes, but both retinas are physiologically implicated in the action. This may be illustrated by the following hypothetical schema: The schema represents the relation between the retinas during a single succession. It is given that two half-images, f_1-a_1 and f_2-a_2, follow in succession. At a certain speed of succession the right line a is seen moving backwards. We may assume that the line f is in focus, and seen continuously, while a_1 and a_2 are seen in alternation. First a_1 appears, and is visible during the phases A, B, and C. After a_1, a_2 will appear, and is visible during the phases

D, E, and F. The unbroken lines indicate the visible images; the dotted lines indicate the points in the other retina which have not been stimulated, and to which the unbroken line a_1–a_2 stands in dynamic relation. Every projection of a half-image is, accordingly, divided into three phases. In the first three phases, A, B, and C, the left half-image is united with a continuously changing, non-stimulated position in the other retina. In the phase A, a_1 is linked with a strictly corresponding, non-stimulated point in the right retina. This means that the movement begins in the plane of fixation. In phase B, a_1 stands in dynamic relation to a disparate, non-stimulated point which, in phase C,
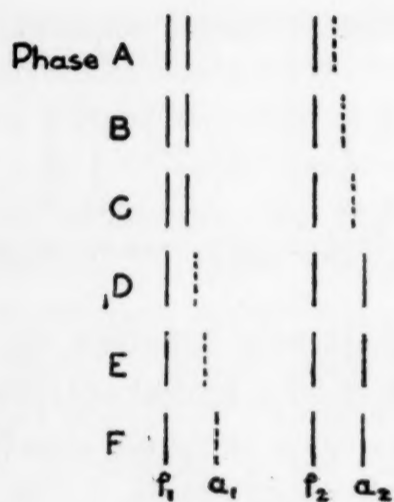

FIG. 30

becomes even more disparate. The visible line has therefore moved approximately to that point, during phases A, B, and C, at which a_2 appears in the binocular field. The movement, in keeping with the unification of the non-stimulated points of the left retina, continues throughout the phases D, E, and F. The plane of fixation, as can be plainly observed, is again reached in phase F. The strongest depth is here supposed to be attained half way through the whole stroboscopic process. The images would be in the plane at the beginning and the end of the process. Such a movement could not be seen if there were too great a speed of succession. (It actually occurs only at a relatively low rate of speed.) Generally, in fairly rapid speeds of succession, neither the beginning nor the end of the movement is seen. In

such cases the apparent movement takes place in a stereoscopic depth which is completely out of the plane. (The case of a completely straight depth movement could be easily indicated by somewhat changing the relations in the schema.) It is a matter of indifference whether the movement starts in the plane, moves out of the plane, and then returns, or whether it completes itself altogether in a straight depth direction. A correct stereoscopic depth is always seen. It is evoked by a simultaneous binocular interaction, that is, by the interaction of disparate points. Such a movement must, accordingly, be distinguished from an alternate-ocular movement, by the fact that each half-image is part of a binocular process. It differs from the ordinary binocular simultaneous vision insofar as the *visibility* of the half-images alternates. What is seen is a depth process in terms of the displacement of the half-images a_1 and a_2, as conditioned by the dynamic relation of the line to changing non-stimulated points in the other eye. This gradual change in disparity can be considered as the basis for the visible depth effect.

(2) *Binocular effect with respect to time:*

The experiments have shown that the transition from alternate-ocular perception to binocular perception depends on the rate of succession. The previous discussions have attempted to demonstrate how the strobostereoscopic effect, as such, may be explained. A further attempt shall now be made to explain the relation between depth effect and the speed of succession.

Two sets of facts indicate that the binocular stroboscopic process needs a certain optimum in order to develop. These facts are: (1) The gradual arrival at an irreversible, stereoscopically proper, depth. (2) The appearance of a displacement of the half-images with an increase in the speed of succession. So far as displacement is concerned, the relation between the speed of succession and the change of spatial values for the half-images is indicated in two ways: (a) In the increasing mutual displacement of the half-images with an increase in the speed. (b) In the shifting of the phases I, II, and III with the increase of the distance $a-b$ in the double line.

(a) *Increase in the mutual displacement of the half-images as the speed of succession increases:*

This phenomenon can be observed as easily in the single line *c*, as in the double line *a–b*. The single line is seen, so to speak, as a double line at the distance *0*. It is displaced towards both sides as it comes, simultaneously, into relation with the double line. In other words, a single line, as such, can no longer be seen after a certain speed. It is a sign of the binocular interaction that the movement no longer begins or ends in the middle, in the objective position of *c*. The beginning and end are increasingly removed from the middle region as the speed of succession increases, until in the ultimate flicker stage, the movement is maximally removed from the middle region. The double lines on the other hand, tend to displace themselves by means of an interaction with the single line. As shown in the experiments dealing with the shortening of the distance separating the double lines, there is a shortening of this distance with an increase in the speed of succession. The shortening reaches a maximum at the flicker stage. The shortening as a displacement phenomenon must be interpreted as the effect of a binocular assimilation between a " double line " of the distance " zero " and a double line of a certain objective distance. This displacement of both half-images, up to the point where they cover each other in the binocular field, accounts for the flicker phase III.

(b) *Shifting of the phases with increase of distance* **a–b**:

It can be demonstrated by indirect means that the law affirming a direct relation between displacement and the speed of succession holds true. The main experiments have established the fact that, on the average, phase II will undergo the transition into phase III at a speed (σ) that is inversely proportional to the increase in the distance between *a* and *b*. Now, it is obvious that the degree of assimilation between the single line and the double line, *i.e.,* the maximum displacement, is so much the greater when the double lines are farther apart. This really means nothing more than that whenever the maximal displacement is greater, the speed of succession must necessarily be higher : and whenever it is smaller, the speed of succession can be lower.

Schematically represented:

Maximum amount of displacement (flickering)$=$A; distance
$a-b=D_1$; speed of succession$=a$

Maximum amount of displacement (flickering)$=$B; distance
$a-b=D_2$; speed of succession $=\beta$

If $D_1<D_2$, and consequently A$<$B, then the speed $a<\beta$. It
appears, therefore, that *the time factor is an essential condition
for the evocation of a binocular effect.* If we designate the
binocular effect as E, *then E is a function of spatial disparity* (δ),
(*i.e.,* incongruence of the half-images), *as well as a function
of temporal disparity* (τ), (*i.e.,* pause between the successive
images). If δ increases, this increase may be partially compen-
sated by the time factor: phase II is reached at higher speed.
By and by this compensation does not hold; with increase of
distance $a-b$, phase III and finally phase II is never reached. If
the "τ" factor becomes larger and larger, the binocular effect
becomes less and less, until it finally vanishes.

The general grounds for the absence of binocular effect in a
diminution of the speed of succession, as for the increase in the
distance $a-b$ are obviously to be found in the dynamic of the depth
process.

Temporal slowness, as well as great spatial distance, lessens
the possibility of a binocular interaction between the two retinas,
that is, lessens the possibility of a unified binocular process in
which both retinas share. It therefore follows that as these
monocular fields become temporally and spatially discrete, to a
higher degree, the monocular configurations will begin to domi-
nate. An alternate-ocular process takes the place of the binocular
process. Each retina reacts by itself to its constellation of
stimuli. One receives an impression of depth movement without
any assimilation (displacement) of the half-images, that is, with-
out any binocular displacement. The movement begins actually
in, or near, the normal monocular space value, and ends in, or
near, the monocular position. In a slow succession, the *O* sees
a movement of maximal amplitude. The higher the speed of
succession, the more will the monocular efficiency diminish.
Along with this, there appears a binocular displacement as the

expression of an assimilation of half-images. In certain zones of succession, sometimes the monocular and then again the binocular process is predominant. The binocular depth movement competes with the alternate-ocular until, at a sufficient speed, it becomes alone predominant. ·(There is nothing to prevent the assumption that, in critical zones of movement, the single depth processes are of a mixed nature. At a certain speed it is quite possible that the process is partly binocular and partly alternate-ocular.)

3. *Strength of dynamics with respect to strobostereoscopic effect:*

(a) *Experiments with the dot-pattern:*

This type of pattern (Fig. 23, 2), as we have already mentioned, differs from the conventional Panum-pattern in that the single line *c* stands in a closer dynamic relation to the double line *a–b*. The splitting up of the single line can be directly perceived, and tests can be made to determine the extent to which the single line is really bound to the double. The main question to be answered is whether the three phases are influenced by the introduction of such a pattern which provokes a more intense relation between the two half-images.

The general results which are attained by the use of the dot-pattern are as follows: (1) The three phases appear in the same order as they did in the basic pattern. This succession is likewise dependent on the relative speed of succession. (2) *A genuine double relation of the single line to the double line is now clearly visible.* The points 1, 3, and 5 will move rapidly to one side, and the points 2, 4, and 6 will move to the other side. This also holds true for the preliminary phase, in which the movement is fulfilled in the plane. In phase II, the depth movement of each set of three points in opposite directions is still seen. This movement becomes increasingly more limited in extent, until finally the stage of flickering is reached. Phenomenally, let it be noted, there is not a set of triple points, but two " lines " consisting of three points that have separated, and moved to opposite sides, from a " line " composed of six points. (It

may be assumed that there is much the same situation present
when the full-line-pattern of the Panum-phenomenon is used.)
(3) With the use of the dot-pattern, phase II is reached at a
lower speed of succession than that which was needed to produce
the same effect with the basic pattern. In the following table
are given the lower speed limits (in terms of succession time
between the two exposures) for the dot-pattern as set over

TABLE XII

Indicating the 3 Stages Dot-Pattern vs. Basic Pattern

Subject	S_1					S_2		
Distance	4 mm.		5.5 mm.		4 mm.		5.5 mm.	
Pattern	Basic	Dot	Basic	Dot	Basic	Dot	Basic	Dot
Stage I (σ)	700	675	675	675	675	700	675	675
Stage II (σ)	225	325	200	275	400	425	250	300
Stage III (σ)	125	125	100	100	150	150	125	125

Subject	S_3					S_4		
Distance	4 mm.		5.5 mm.		4 mm.		5.5 mm.	
Pattern	Basic	Dot	Basic	Dot	Basic	Dot	Basic	Dot
Stage I (σ)	400	450	325	375	525	550	450	450
Stage II (σ)	300	350	125	200	400	425	300	350
Stage III (σ)	125	125	75	100	175	175	100	125

Subject	S_5			
Distance	4 mm.		5.5 mm.	
Pattern	Basic	Dot	Basic	Dot
Stage I (σ)	650	650	625	650
Stage II (σ)	300	325	250	275
Stage III (σ)	175	150	125	125

against the analogous speeds for the basic pattern. Average
values are recorded for the two *a–b* distances 4 mm. and 5.5 mm.
Phases I and III are apparently but little affected by the change
of pattern.

How shall we account for the relatively early appearance of
the second phase? Since this stage is based on a genuine stereo-
scopic effect, it must be assumed that the *dot-pattern is provo-
cative of the binocular process to a higher degree than the basic
pattern*. This hypothesis is in full agreement with the results
gained by the use of the simultaneously exposed, stereoscopic
dot-pattern in work with the thread apparatus. As one recalls,

in the experiments with the thread apparatus a stronger depth effect is attained by means of the dot-pattern. We tried to explain this fact on the basis of a more intensified relation between the two half-images. An intensified tendency towards identification of the single line with both sides of the double characterizes this effect. The heightening of the depth effect in the strobostereoscopic experiments by the introduction of the dot-pattern very probably is due to the same cause.

(b) *Experiments with the stair-pattern:*

Experiments with the stair-pattern (Fig. 23, 3) yield the following results: The three phases are noted by all observers. In the first phase, the single line undergoes transformation into a three-dimensional stair-like form which makes a partial rotation out of the plane about the middle point. This partial rotation
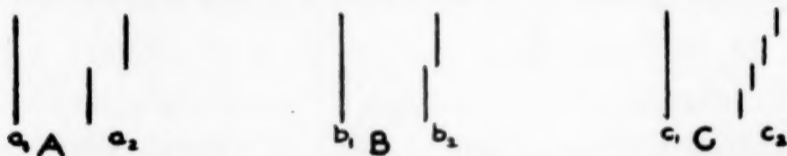

FIG. 31. Stair-patterns used in strobostereoscopic experiment.

is reversible. The single line disappears in phase II. The stairs turn in a manner in keeping with the "correct" stereoscopic depth position. That is: The lower part of the figure moves backward; and the upper, forward—or vice versa. In phase III the steps are seen in the "correct" stereoscopic position, and flicker. The depth effect in all these cases is based on the same principles as those applying to the dot-pattern. The single line divides in such a way that its parts become identified with portions of the other half-image. The only difference in this case is that the second half-image does not have *one* distance (cross-disparity) separating it from the single line c as does the half-image of the dot-pattern; there are *two* distances at both sides. The question arises whether the dynamic *process of depth movement, as expressed in the speeds of succession for different phases, is based on the lesser or the greater distance.* In order to find a reasonable answer one may resort to the device of comparing the stair-pattern C with two other patterns. These two patterns are derived from the original figure by removing the inner, resp. the outer, lines of the stair-pattern (Fig. 31).

For the sake of brevity only the speeds of succession for phase II in the three cases A, B, and C are compared (Table XIII).

It is revealed in this table that, in the majority of cases, zone II is reached at a speed of succession which, for pattern C, is between the speeds of A and B. *The stereoscopic effect of a pair of lines is enhanced, accordingly, in the event that these lines are related to certain parts of the field which themselves attain a depth effect more quickly. In case they are related to parts of the field which are characterized by a retarded depth effect, then they, too, will be held somewhat back. In other words, the binocular*

TABLE XIII

INDICATING STAGE II (IN σ) BY USING STAIR-PATTERNS A, B, C

5 O's

Subject	Pattern A	Pattern B	Pattern C
S_1	300–125	250–100	275–125
S_2	400–150	300–125	350–175
S_3	350–125	200–100	275–125
S_4	400–150	325–125	325–125
S_5	325–125	250–125	300–150

dynamic of a part is dependent on the dynamism which governs the whole binocular field.

4. *Diversity in half-images with respect to strobostereoscopic effect:*

(a) *Experiments with the zig-zag pattern:*

One possible method of differentiating the half-images in order to observe them more closely during the process, is that of making them distinctly different in geometrical form, or in color. In these experiments, the geometrical forms of the two members of the pattern are distinctly different. One of them is in the form of a zig-zag line, and the other is a double line (Fig. 23, 5).

General results: (1) The three phases succeed one another in much the same way as in the basic pattern. (2) There are certain phenomena which are of special interest. During the first phase the zig-zag line splits and is seen moving towards both sides, changing into straight lines while moving. This change occurs during each successive projection of both half-images

anew.   In phase II the movement no longer begins (or ends) in the middle region.   Always *two* lines are seen in motion.   Different *O*s record various phenomena as characteristic of this movement: With each exposure both lines are seen first as wavy, and then become straight (case *A*).   Again, one moving line is straight, and the other zig-zag in form (case *B*).   Or both moving lines are partially wavy and partially straight (case *C*). If the observer looks sharply, in this last instance, he sees that the situations of the single lines are alternate.   This means that the section of the one line, to the left or right, which corresponds to the straight part of the other, will be zig-zag in form, and, of course, the reverse holds true.   If the movement is accelerated, all the observers see two more or less wavy lines in motion.   The
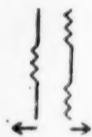
Fig. 32 (case *C*)

"zig-zag" characteristic is less pronounced (*i.e.*, more wavelike) compared with the single zig-zag line as seen with one eye (case *D*).

Both lines are wavy in phase III.   This waviness is often diminished up to the point where the lines will show but slight disturbance in their quality of straightness ("roughness").

These experiments, in which the two half-images were clearly distinguishable in their geometrical forms, indicate unequivocally that the half-images are actually displaced by a binocular process in strobostereoscopic exposure.   The results gained from the experiments in which a basic pattern was used are now given definitive corroboration.   Case *A* shows that the binocular process is actually effective when there is an alternation of stimuli first in one eye, and then in the other.   The wavy line is *visibly split and displaced towards both sides,* a phenomenon which seems not possible if there were not continuously changing, non-stimulated points in the other retina which stand in simultaneous, disparate correspondence.   The irreversibility of the depth movement denotes that we do not have here an alternate-ocular process. Case *B* is more complicated; the one half-image is here visibly

involved in the binocular movement of the one side; the other half-image carries the movement to the other side. This displacement can be easily explained by the relation of each half-image to an invisible point in the other eye. In case *C*, the binocular movement (which is of a very small amplitude) is carried by both half-images in both directions. In this case, therefore, the half-images have a fragmentary visibility in the binocular process. Case *D* exhibits binocular intermingling of both the half-images. The distinctive property of the zig-zag line, that is, its zig-zag character, comes into dynamic relation with the analogous property of the double line, that is, its straightness. The half-images are, accordingly, not only with reference to their spatial position, but also with respect to their figure quality visibly subject to an assimilation. Case *D* shows once again that there is a visibly double relation of the single line to the lines of the other half-image.

It is not easy to give exact reasons for the appearance of this double relation, which, it might be added, underlies the typical form of the Panum-effect. Since this *D* phase develops out of the *C* phase, perhaps the simplest explanation would be that smaller parts of the single line combine with smaller parts of the double line. If this possibility is tenable, we are again dealing with the same process of unification which was present in the dot-pattern experiments. From this interpretation the hypothesis may be derived that the double relation in the normal Panum-phenomenon also originates in the splitting off of different parts of the middle line which may become related to either side of the double line. Whatever it may be, the experiments with a pattern made of diversely formed figures show that such half-images are actually displaced, obviously because of their relation to invisible points in the other retina, and consequently give rise to a precisely binocular depth movement.

(b) *Experiments with the bow-pattern:*

These experiments are obviously related to those with the zig-zag pattern. Results: A revolving-door movement of the bow (Fig. 23, 4) is seen in phase I. For the most part the bow is seen in a position that it stereoscopically " correct " (*e.g.,* convex or concave). The observers often see two bows, though usually only one bow and one straight line. Both lines are usually bent in phase II. The one line curves somewhat in front of the other, according to the typical Panum-phenomenon. This doubling of the bow is seen only in case the pair is conceived as a whole. In phase III, usually only two bent lines are seen. They lie at a depth which corresponds to the depth of the Panum-phenomenon

(that is, the depth of the P.-phenomenon which would result from a simultaneous projection of half-images).

Even at a slower speed of succession, such as 500σ, the bow is moving into the stereoscopically " correct " position, a fact which indicates that each image is in itself displaced in consequence of a binocular process. This means that the half-image stands in a dynamic relation to changing points in the other retina. A schematic representation analogous to the one given in Fig. 30 may serve to illustrate this fact for the simple case: |←).
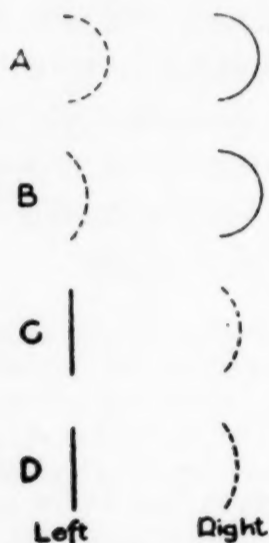

Fig. 33. Diagram, explaining strobostereoscopic effect in case: ←).

In this figure, the unbroken line indicates the actual stimulus, and the dotted line, the points of the other retina which are supposed to be in binocular relation to the full line. The successive phases A and B (arbitrarily chosen) show schematically the points in the left eye which are linked with the visible right hand image. The phases C and D illustrate the relation of the left visible half-image to the right retina. In spite of the fact that there is only one half-image visible, the depth movement is guaranteed by the continuous interaction of the two retinas.

In the higher stages II and III, not only one, but two, bent lines, one in front of the other, are seen in the depth movement. This indicates that both straight lines are in dynamic relation to the one bowed line. The explanation of such a double relation will be found to be substantially the same as that given for a similar situation where the zig-zag pattern was used.

PART IV

Depth and Displacement in Fragmentary Binocular Vision

There is weighty evidence supporting the hypothesis that stimulated points in one retina can become dynamically united with non-stimulated points in the other, both, then, possessing " identity of visual direction ". This evidence is based on facts dealing with the phenomena of stereoscopic and strobostereoscopic fragmentary images. Fragmentary half-images are constructed in such a way that one half-image or both are incomplete to an extent that there is only a partial relation between stimulated points of the two retinas.
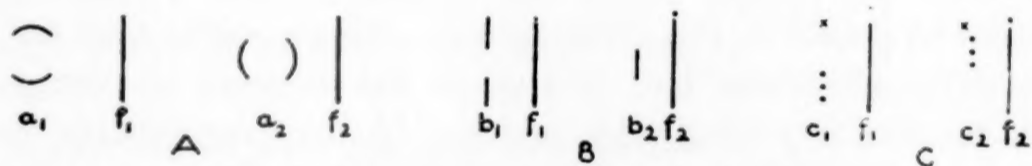

Fig. 34. Fragmentary stereoscopic pictures.

1. *Observations with the stereoscope:*

Some of the figures which were used in these observations made with the Brewster stereoscope are reproduced in Fig. 34.

Trained observers have little difficulty in uniting the images. In case A, a complete circle is seen; in case B, a twice-broken line; and in case C, six points one over the other.

Van der Meulen and van Dooremaal[16] carried out some experiments which are fundamentally concerned with the stereoscopy of fragmentary half-images. Hering's ball-dropping experiment was varied in such a way that, by means of the interposition of prisms, the half-images of the falling ball were not in a horizontal line as usual but one above the other. According to the results of these investigations, there is a clear, though somewhat weaker, apprehension of the relative position of the ball as it drops either in front of, or behind, the fixation point. The object is presented by means of half-images which, in

[16] Stereoskopisches Sehen ohne korrespondierende Halbbilder, *Arch. f. Opth.*, XIX, 1, 1873, p. 137.

consequence of their position, one higher, the other lower, do not have corresponding points of stimuli in the other eye. These experimenters conclude that the perception of depth is based on a purely psychic factor: interpretation, since the psycho-physiological factors which lead to depth effects in normal binocular vision are missing. This conclusion seems to be, however, not justifiable.—R. Dahlmann [17] also worked with defective images which he presented by means of a stereoscope. He, too, on the basis of these and other experiments, comes to the conclusion that disparity, over against the psychic factor of configuration, is not a necessary factor in depth perception. K. Koffka [18] constructed a pattern on the principle of fragmentary half-images. He especially employed this pattern to illustrate the rôle of the dynamic gestalt factor in the binocular process.

These simple experiments indicate definitively that, under special conditions,[18a] the half-images will lose their " normal " visual direction, even when there is no corresponding point of stimulus in the other eye. The change in visual direction, as I see it, can be understood only by the assumption that there is a
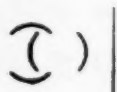
$$\mathcal{I} \;) \; \big|$$

Fig. 35. Binocular picture of two imperfectly combined half-images.

relation to points in the other retina. These points may not be objectively stimulated but, because of the tendency to configuration, become physiologically active. If the fragmentary half-images are completely unrelated, then each half-image is linked to a strictly corresponding, non-stimulated point in the other retina. Under these conditions, there is no depth effect. If these fragmentary half-images are perfectly combined, there is an identity of visual direction of each half-image with respect to non-stimulated disparate points in the other retina. Depth results from this. Depth can also appear in an imperfect combination (as shown in Fig. 35), which indicates that it is not the complete unification of the half-images into one gestalt, but the displacement resulting from the gestalt tendency which is the really effective factor. In the following figure the half-images of pattern *A* are incompletely combined, that is, they have not yet attained the maximum displacement. In spite of this fact, the depth effect is clearly visible to most observers.

[17] Querdisparation und Gestaltauffassung, *Arch. f. Psychol.*, 1934.
[18] *Principles of Gestalt Psychology*, 1935, p. 271.
[18a] In this case: the tendency to integrate the parts into a configurated whole.

There are various objections to this explanation. It might be contended that the relative displacement and depth of fragmentary half-images are not conditioned by the relation between stimulated and non-stimulated points of the retina, but that they are the result of disparately unified focus lines, f. By the introduction of any kind of distinguishing mark in the upper half of the focus line (vid. Fig. 34, B, C) it is possible to decide the question. If the two marks lying one above the other are in vertical relation with the united lines f, the double or single image of the combined figure will, in spite of this fact, appear at a different depth than that of f. This goes to prove that the disparity of f is not the sole factor underlying depth perception, but that a depth factor must be intrinsically present in the images themselves. Further, still, displacement of the half-images can be made clear in the following manner: If both half-images of pattern C in Fig. 34 are marked with an "x", in such a way that the united x appear in the plane of fixation, skilled observers will report a displacement of the dotted line of the right half-image with respect to the binocular mark x.

2. *Experiments with the strobostereoscope:*

Experiments with fragmentary images as seen through the strobostereoscope are perhaps even more definitive in their results than the experiments we have already discussed. Two patterns, for the most part, are used in these investigations.
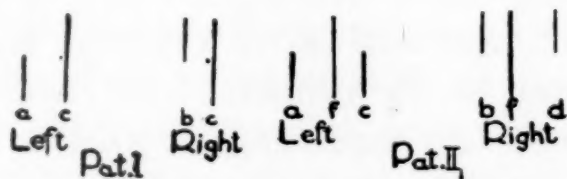

Fɪɢ. 36. Fragmentary patterns used in strobostereoscopic experiments.

General results with pattern I:

Pattern I was presented in all possible combinations. The point near c is continuously projected during the whole strobostereoscopic observation, and is the visible focus point. As in all strobostereoscopic experiments, the succession of the half-images is repeated several times.

(1) All 4 observers report three characteristic phases dependent on the relative increase in the speed of succession.

Phase A: In a relatively *slow succession, a movement of the half-line in the binocular field is seen to proceed diagonally from below upward* (or in a reversed succession, from above downward).

Phase B: As the speed of *succession increases, the diagonal direction of the movement becomes more and more vertical, until finally, after a certain speed, the movement of the half-line occurs in complete verticality.*

Phase C: If the speed of succession is *increased still further,* a phase will be reached during which *both half-lines are seen simultaneously without movement.* There is no visible displacement. The half-lines appear in the binocular field at a distance from the main line *c*, in correspondence to their monocular position.

FIG. 37. Three phases in strobostereoscopic experiment with fragmentary half-images (Pattern I).

Phases *A, B,* and *C* are different, with respect to speed of succession, for different observers. If pattern I, as illustrated above, is employed, the time-intervals between the exposure of the left and right hand images (Phase *B*) are those of table XIV.

(2) As in many other instances of stroboscopic phenomena, the phases are not dependent on the objective stimulus alone, but are also conditioned by the attitude of the observer. The limits of the second stage vary depending on whether the conditioning critical speed of succession is arrived at after a gradual decrease from a higher speed, or after a gradual increase from some speed of succession within phase *A*. The lower limit of phase *B* is characterized by less speed when the speed of succession has been reached by gradual reduction, than when it is the result of a gradual increase within phase *A*. The significance of this dynamic attitude is illustrated by the fact that, between phases *A*

and *B*, there is a critical zone, in which the observer can voluntarily choose to see either a diagonal or a vertical movement.

(3) In most cases of phase *B* there is an *increased shortening of the total distance traversed by the half-line* concomitant with the increase in the speed of succession. The movement no longer begins and ends strictly at the top and the bottom, but is more or less shortened towards the middle.

(4) *The nearer the diagonal movement approaches the vertical, the more the half-images are displaced towards a line which lies in the middle region between the two monocular directions of the images.* In other words, the displacement of the path of movement in phase *B* is the expression of a displacement to which both half-lines are equally subjected. The situation may be demonstrated by the following diagram:

FIG. 38. Diagram showing displacement effect in strobostereoscopic movement.

Points *l*, which are continuously visible, are chosen in such a way that points *l* and *f* are in the plane of fixation after the images are unified. The path of movement in strobostereoscopic projection will lie either exactly through these points, or a little to the right or left of them. Both lines, as one may notice, have about the same share in the displacement.

(5) The depth effect which, as such, is relatively less pronounced in any strobostereoscopic projection, becomes more diminished still when fragmentary half-images are used. Two of the four observers see the half-images before or behind the plane of fixation, corresponding with the displacement.

General results with pattern II:

All in all, the results attained by the use of pattern II tally with the results gained with the use of pattern I. In phase *A* there is the same diagonal movement to both sides of *f*, a move-

ment which, in phase *B,* gradually becomes a vertical, parallel movement. The long line *f* appears at a middle distance between the two paths of movement. Phase *B* is reached more quickly with pattern II as compared with pattern I (Table XIV).

Theoretical discussion of the results. The problem of monocular diplopia:

Strobostereoscopy shows more clearly than the simple stereoscopy with fragmentary pictures that half-images are displaced by means of a change in their relation to non-stimulated points in the opposite retina. The origin of strobostereoscopic displacement is obvious. Displacement is determined by the tendency of both half-images to unite dynamically. *The expression of unification is not, in this case, the fusion of the two half-images,*

TABLE XIV

INDICATING THE RELATION BETWEEN PHASE B AND SPEED OF SUCCESSION

Observer	O 1	O 2	O 3	O 4
Pattern II, Phase B:	450–145σ	480–135σ	500–125σ	500–130σ
Pattern I, Phase B:	280–155σ	350–145σ	300–125σ	300–125σ

but their movement: " One " half-line moves in the binocular field. This tendency to binocular unification gradually affects the whole path of movement, and a vertical movement results. *It is also characteristic that, should this dynamic relation between the half-images cease* (phase *C*) *the displacement immediately vanishes.* There are accordingly two possibilities in the critical phase between *B* and *C*: (a) A movement from a downward position upward (or vice versa). In this case the displacement is at its maximum. Or, (b), the half-images may be seen almost simultaneously and at rest. In this latter case, the displacement immediately ceases, and both images appear at different distances with respect to the focus line.

In these experiments there were two observers who reported seeing a phenomenon which represents a special instance of the displacement effect, and which is obviously related to the so-called " monocular diplopia " phenomenon. In phase *B,* when

the movement is vertical, and the displacement is at a maximum, one observer regularly recorded a diplopia effect, and another reports it occasionally.   If the observer concentrates his attention on the under part of the half-line in its movement upwards, the line appears not only in a position that is monocularly " correct ", but also in a displaced position.   The result is, that the *O* receives the impression of a double image of the one, monocularly visible half-line—or at least of parts of the half-line.   The phenomenon is so remarkable that the *O*s report actual bewilderment.   It can be seen also on the upper half-line, providing that this part of the line is moving in a downward direction.   Sometimes the phenomenon occurs in such a way that a horizontal movement is seen simultaneously with the vertical movement.   This means that there is a movement from left to right (from the non-displaced side to the displaced side), and another from below upward (corresponding to the normally observed, strobostereo-scopic phenomenon).

Fig. 39

It follows from this phenomenon that, under the particular conditions of the experiment, the half-line *a* must have a quasi-simultaneous relation to two points in the other retina.   We may term this phenomenon " experimental monocular diplopia ". Monocular diplopia, as it is called, is a phenomenon that has been investigated thoroughly by Tschermak[19] and Bielschowsky[20] in individuals who, after an operation which has relieved them of squinting, are learning how to see in the normal way.   Those suffering from strabismus who do not avoid binocular diplopia by suppression of one eye, are able to see singly because of an abnormal correspondence that develops between the two retinas. This abnormal identity of points in the two retinas differs from normal identity up to the extent of the angle of the squint.

[19] Über die anormale Sehrichtungsgemeinschaft der Netzhäute bei einem Schielenden, *Arch. f. Ophth.*, 47, 1899.
[20] Untersuchungen über das Sehen der Schielenden, *ibid.*, 50, 1900.

Certain points, which for normal eyes do not correspond, are identical for the squinting person. The squinting individual adjusts correspondence to the abnormal process of fixation, and develops what has been called an " abnormal community of visual direction ". It can be shown, by means of the nonius-method, for example, that vertical lines, which, for normal eyes, appear double, actually lie in the same visual direction for the person troubled with a squint. There are some cases of persons suffering with squint-eyes who, after an operation which relieves the condition, must learn how to see in the normal way, and who, during this period of readjustment develop a monocular diplopia. This phenomenon has been described with particular clarity by Bielschowsky (*l.c.*, 455 ff.). The monocular diplopia thus described in the case of one of the patients, acts in such a way that an object visible to the left eye alone appears as a double image separated by as much as 20°. This monocular diplopia vanishes as soon as the other eye is closed. (Because of this fact, a monocular after-image will never appear diplopic.) It is only when the other eye retains the freedom of fixation that the monocular diplopia appears. These facts seem to indicate that monocular diplopia arises through a binocular process. One and the same point in the one eye shares a community of visual direction with two points in the other eye. Both these communities of visual direction represent the " old " abnormal community of visual direction, as it existed in the retinas before the operation, and the " new " visual direction, when the eye has learned to see anew in keeping with the now normal vision as corrected by the operation.[21] It is significant for this understanding of the situation that the more the patient practised the more the monocular diplopia diminished in effect. Monocular diplopia was present so long as the conditions governing both kinds of correspondence, normal and abnormal, were of equal importance.

Let us return to our experimentally evoked monocular diplopia. The same explanation seems to apply in this case. The phenomenon of monocular diplopia is here only temporary, but the

[21] In our terminology (vid. Part V) we should say that the primary zero correspondence has changed.

conditions which control its appearance may very well be the
same. It can be readily conceived that the fragmentary half-
images, as seen through the stroboscope, provide a weaker
stimulus to disparate correspondence than do the fully developed
stereoscopic images. It is because of this weaker stimulus,
especially during the inception of the image first projected, that
a conflict arises between " normal correspondence ", such as
would be dependent on a strictly monocular perception of the
half-images, and " disparate correspondence ", such as would be
characteristic of the binocularly displaced half-images. The
result of this conflict is " monocular diplopia ".

PART V.

DISPLACEMENT AND THE DYNAMICS OF THE BINOCULAR FIELD

In the preceding chapter it was shown that displacement, which is based on disparity, is a necessary factor in the binocular perception of depth. May it not be true that displacement is not only necessary, but also a sufficient reason for a binocular perception of depth? We shall see that this question will receive a negative answer, providing that displacement is conceived in a static, "objective" sense, but that it can be answered in the affirmative, if displacement is conceived in a dynamic, process-like sense.[22]

(1) *Displacement as effect and displacement as process:*

One of the best known facts of stereoscopic perception is that, by using a stereoscope, the perception of depth in simple figures presents difficulties, especially when the observers are untrained. In the German translation of Wheatstone's "Contribution to the Theory of Vision" in Poggendorf's Annalen, Supplement No. 1, 1842, it was already expressly emphasized that there existed a difficulty in the perception of stereoscopic effects when the observers were not properly trained. The translator says, "since I was not practised in the use of the stereoscope, and the effect which it occasions, both drawings (non-concentric double circles to the left and right) appeared to me simply as a smaller and a larger circle, both of which had a common center. I saw them both in the same plane. Only when the relief was pointed out to me, did I become aware that the inner circle was nearer. The same happened to each other observer . . . ". Difficulties in stereoscopic perception, naturally, may originate in the fact that

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[22] As far as the general conception of dynamics in binocular depth vision is concerned, I find myself in high agreement with K. Lewin and K. Koffka. Vid. K. Koffka, Some problems of space perception. *Psychologies of 1930* (ed. by Murchison), 1930.—*Principles of Gestalt Psychology*, 1935, 265.— Lewin, K., and Sakuma, K., *Psych. Forsch.*, 1925, 6, 298 ff.

the observer does not properly unite the image, or that he suppresses one eye, etc. However, if we practice precautionary measures, that is, if the lines are drawn in different colors, while we employ a simple pattern, such as that represented in Fig. 40, the presence or absence of a geninue binocular fusion can be readily demonstrated. It is a well known fact that a sensibility for the perception of depth in such simple figures must be

Fig. 40

acquired, and that some observers with perfectly normal vision can never do this, despite a serious effort on their part.[23] Here is a case where there is a not inconsiderable disparity, where the adequate displacement can be directly demonstrated, and yet where, in spite of these conditions, there is a negligible depth effect, or none at all.

Inhibition of the depth effect can be fundamentally increased if the pattern is changed in such a way that it represents a sort of frame by the addition of horizontal lines. Here, again, displacement in fusion can be demonstrated by placing marks in
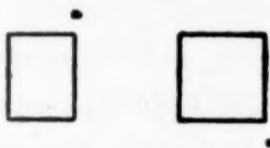
Fig. 41. Frame pattern.

the upper and lower corners. In spite of an actual displacement proved by these distinguishing marks, it is impossible for some observers to see the frame partially turned out of the frontal parallel plane. Even though it is true that, in most cases, those observers can ultimately perceive stereoscopically, the question still remains as to just what is this training. Why, in spite of training, is the depth effect relatively small in such patterns?

An insight into the grounds for the lack of depth effect will be gained by the use of a line pattern originally used by Helmholtz

[23] The contention of some investigators that no depth at all is seen when the pattern of Fig. 40 is used, is naturally too dogmatic.

in connection with a critical report on the Panum correspondence theory.[24]

Fig. 42 consists of two groups. The outer lines of each group to the left resp. to the right are equal, that is, *1, 3=4, 5* and *1', 3'=4', 5'*. Furthermore, *1, 2=1', 2'*. If the binocular figurations *1, 2, 3* (focus in *1*) and *4, 5* (focus in *4*) are alternately fixed, the right outer lines, which have the same disparity relative to the focus in both groups, will usually appear at different depths. The binocular line *3* has a greater depth than line *5*. Helmholtz, without entering into a discussion on this difference of depth, shows that, in the *1–3* constellation, line *3* usually appears as a double image, while line *5* in the *4–5* constellation usually appears as a completely united line. In other words, the field *1–3* is divided into two parts by the middle line *2*

FIG. 42. Helmholtz's arrangement of stereoscopic lines.

in such a way that the disparity refers only to the part *2–3*. The result of this is that *3* easily divides into a double image. What is the difference between the two constellations, from the standpoint of a binocular process? The difference is that, in the case of *4–5*, the displacement necessary to occasion a congruence of both images is easily reached and maintained, while in the case of *1–3* it is attained and held with greater difficulty. In one case there is a stable, and in the other an unstable, displacement. It would seem to follow from this, that an immutable, stable displacement is not a factor in depth. It is only when this displacement becomes labile that a depth effect follows. Expressed in another way, *it is not the displacement as such, but the process of displacement, which appears to be the decisive factor in the phenomenon of depth effect.* It is in accordance with this assumption that an increase in the stability of the pattern—such as in the frame-pattern mentioned above—causes a still greater

[24] Helmholtz, *Physiologische Optik*, 3'd Edit., 1910, III, 374.

loss of depth.   It may be expected, therefore, that an increase
in the lability of a constellation will be provocative of a greater
depth effect.   Such a labilization, that is, the release of the
rigidity of displacement, and the carrying out of the displacement
process, is possible both in the subjective and the objective sense.
Objectively: The stronger the link between the half-images,
an attachment governed by the " law of nearness " (small dis-
parity), and by the " law of equality ", the more stable the
binocular configuration.   On the subjective side, as Hering [25],
and more recently W. Poppelreuter [26] and E. Jaensch [27], empha-
sized, differences in depth vanish more and more as the rigid
fixation in simple stereoscopic configurations continues.   Grad-
ually the images more or less approach the plane of fixation.
Fixation, therefore, diminishes depth perception.   Eye-move-
ments, or objective movements of the objects, strengthen it.
These phenomena are easy to explain, if it is assumed that it is
not displacement as such, but the process of changing the space
values, that is the basic equivalent for the depth effect.   The
stability of the binocular figure is strengthened by concentrated
fixation, that is, by the rigid maintenance of a definite binocular
relationship.   In such case the displacement remains constant.
When there are movements of the eyes, on the other hand, a new
process of displacement is being constantly introduced (vid. the
paragraphs concerned with " velocity parallax ").   The same
applies to objective movement.   By the steady change in fixation
the process of displacement is started over and over again.
Because of this a vibratory movement of the stereoscope rein-
forces the depth effect and makes it much easier for the untrained
*O*s to see a distinct depth.

F. B. Hofmann [28] has attempted to explain the diminution of the depth effect
through fixation as a fatigue phenomenon.   His notion is that the " depth
perception, which has become fatigued by fixation " is " refreshed " by move-
ments of the eyes.   Such vague explanatory methods can be avoided if one
takes the displacement process as the basic factor in the perception of depth.

[25] Hermanns *Handbuch der Physiologie*, 1880, 542, 2.
[26] Beiträge zur Raumpsychologie, *Zsch. f. Psychol.*, 1911, 58, 250.
[27] Über die Wahrnehmung des Raumes, *ibid.*, Suppl., VI, 1911, 92 *et seq.*
[28] *l.c.*, 437.

It seems to me that this theory serves as a means of resolving the paradox which bothered such a distinguished scientist as Hofmann.[29] This paradox is the well-known fact that binocular images which are *momentarily* illuminated will exhibit depth (Dove,[30] inter alia), while stereoscopic images which are observed over a period of time, need a certain preliminary period in which to develop. This contradiction is explained with comparative ease, so I believe, if one makes the following hypothesis: The momentary presentation of images (only, of course, when they are of a clear, easily conceived organization) isolates, to a certain degree, those phases in which the disparate images are first unified. In these first phases, then, the displacement is a process. Once the displacement is completed, and the figure has become stable, that is, if it is easy to hold the images united, the depth effect will then be missing. There is no difficulty in assuming that, in the continuous observation of the images, the first very brief phase is overlooked. Depth effect in continuous observation is reached only when the observer is at last able to release the fixed relation of the stable figures (by means of slight eye-movements, for example), in order that the depth process may be continually renewed. Karpinska's [31] observations relative to this subject agree with the theory which we have proposed. According to her investigations, after one phase of continuous observation, during which the stereoscopic picture appears to be flat, there follows a period of " unrest ". After this phase of unrest, there usually comes the three-dimensional phase.

On the other hand, however, Karpinska has tried to show that under all circumstances stereoscopic images are first seen flat (at a time of exposure of 1/15 sec.) and are seen as three-dimensional only after continued projection. This would contradict the experiments of Dove and other observers.

[29] *l.c.*, 435.

[30] *Ber. d. Berliner Akad. d. Wiss.*, 1841, 252. Vide, in corroboration of Dove's experiments: von Recklinghausen, Zum körperlichen Sehen, *Poggend. Annal.*, 114-, 1849.—Panum, Physiologische Untersuchungen über das Sehen mit zwei Augen, 1858.—Volkmann, *Ber. Verhand. Kgl. Gesellsch. d. Wiss.*, Leipzig, 11, 1859, p. 90.—Aubert, *Physiologie der Netzhaut*, 1865, 315.—Recently: N. M. S. Langlands, *Trans. Opt. Soc.*, 28, p. 45, 831, 1927.

[31] Experimentelle Beiträge zur Analyse der Tiefenwahrnehmung, *Zsch. f. Psychol.*, 57, 1910, p. 15 *et seq.*

G. Skubich [32] has pointed out, however, that the results attained by Karpinska are to be partially explained on the basis of the experimental set-up. The observers are not strictly accommodated to the fixation point immediately before the presentation of the images. Skubich found that if the fixation is exact, a configuration of two or three dimensions will develop out of a form which has *no definite localization* in space.

With respect to the experiments of Skubich, it must be assumed that, in the experiments of Dove and his followers, whether due to the simplicity of the patterns used, or to the fact that the observers were accustomed to them, the phase of indeterminate localization does not appear at all. Because of this, the organized process of displacement can develop immediately. When more complicated stereoscopic forms are used, the points of the left and right retinas which belong together must be selected in order to bring about the proper relationship and this establishment of identity guides and controls the binocular fusion. The fact that often such an establishment of a specific relationship by means of selection is necessary is well illustrated in the cases where there is an ambiguity in binocular configuration: The patterns employed here permit a unification in three ways. In combination *A* the wavy image appears in front of the line of fixation; in combination *B*, it is on the line of fixation; and combination *C*, it is behind the line.
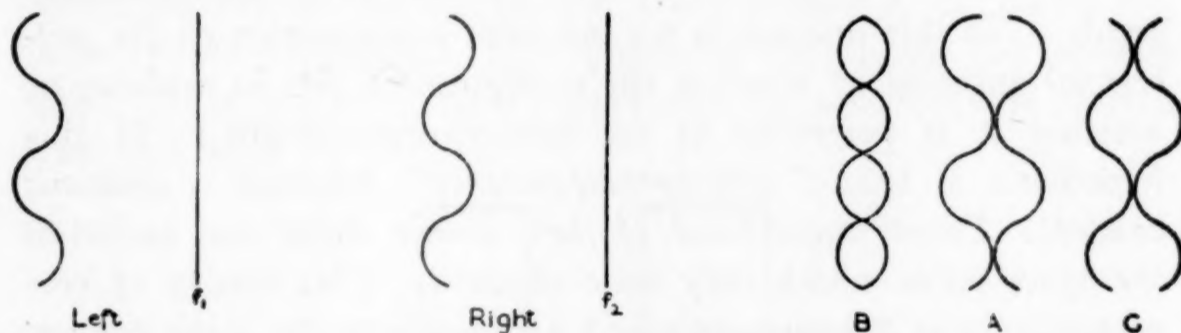

FIG. 43. Ambiguous stereoscopic pattern with 3 possible combinations, A, B. C.

(2) *The dynamic concept of correspondence and disparity:*

(a) The concept of *" zero-correspondence "* :

The concept of " correspondence " is equivocal when it is not determined by two different properties. In Hering's concept of correspondence, two points correspond when (1) *a single, binocularly visible point* arises from the interaction of the two points (*identity of visual direction*), and (2) when this point appears in *the plane of fixation*—that is, when it has a depth value of *0*, relative to this plane. Correspondence, in Hering's use of the term, must always have these limiting characteristics. We should like to call this type of correspondence *" zero-correspondence "*.

[32] *Experimentelle Beiträge zur Untersuchung des binokularen Sehens*, ibid., 96, 1926.

One could also speak of a *" depth correspondence ",* in case the second characteristic was lacking. *Zero-correspondence,* according to Hering, *is determined by the " geometry" of the retina :* there are points which have the same approximate distance separating them—one temporal, the other nasal, in direction from the focal point. Depth correspondence is also geometrically determined. There are measurable disparities on the retina which govern the depth. *Hering's theory, therefore, is primarily geometrical.*

(b) *The concept of " primary and secondary correspondence " and of " primary and secondary disparity " :*

We have arrived at an assumption which is in direct contradiction to the one just discussed. A binocular pattern, in which the displacement, once effective, is stable, does not have any depth. (In this discussion we can omit any mention of the perceptual question of whether the configuration lies in a plane, or whether it is perceived at an indeterminate depth.) If this hypothesis is true, *" zero-correspondence " becomes a dynamic concept. Points correspond, if they remain stable and united at the space value which they have attained. This theory of correspondence is dynamic, in direct opposition to the static concept of Hering.*

" Zero-correspondence ", in accordance with this viewpoint, is characterized by (1) a complete unification of the half-images (common visual direction), and (2) by a maximum of stability, or immutability, in the relative space values of the unified configuration. Hering's conclusions are not negated by these ideas. They are merely included as special instances of the general dynamic theory. The " primary correspondence " of Hering is probably anatomically and physiologically conditioned. In any case, it is a fact that has been demonstrated by countless experiments, and cannot be denied. It is another question, however, whether it, as a fact, can be given a dynamic interpretation: Points with a primary correspondence are points which, possibly as a result of anatomical and physiological conditions (equal visual angles), exhibit a decided immutability in space values during a binocular unification. One consequence of this

hypothesis, which must be tested further by subsequent observations, must be that if zero-correspondence is conditioned not by the geometry of the binocular field, but rather by the dynamic properties of this field, objectively disparate points of the two retinas, which are stably united (at least temporally), should also show zero-correspondence. Such a *"secondary zero-correspondence"*, or, more briefly, *"secondary correspondence"*, would express itself not only by the fact that both points appear in the plane of fixation, but also by the fact that, since there is a new standard for zero-correspondence, there must also be a new standard for "disparity". A secondary correspondence must be attended by a correlative secondary disparity and a secondary displacement. The strongest evidence for the existence of these phenomena would be the transformation of points of primary correspondence into disparate points of the second order. The following figure illustrates the possibility of such a transformation.

Fig. 44. Stereoscopic pictures demonstrating "secondary disparity".

Fig. 44 is so constructed that there is a " frame " of a relatively high stability.

Most observers see the stereoscopic picture in the following way: The frame appears at a slight, sometimes negligible, depth despite the objective disparity according to which the left side of the frame ought to move distinctly forward out of the frontal-parallel plane. The horizontal line, on the other hand, which (being alike at left and at right) should appear in the frontal-parallel plane, actually is turned more or less diagonally with the right end of the line forward. An attempt to explain that transformation of correspondence by means of a diagram is made in Fig. 44a.

Let it be assumed that *1–2* is the left half-image of the horizontal line in Fig. 44, and that *3–4* is the right half-image. The half-images of a point in the frame are denoted by *x* and *y*. At

the same height as the horizontal lines are the focal points *1–3*.
Under "normal" conditions, the points *2* and *4*, and *x* and *x'*,
correspond (primary correspondence). The points *x* and *y*
would then be disparate. The direction of the displacement of
x would then be temporal; *x* and *y* united would therefore appear
behind the plane of fixation, and *2* and *4* in the plane. If, on the
other hand, such a stability is established between *x* and *y* that
they are zero-correspondent, and accordingly appear in the plane
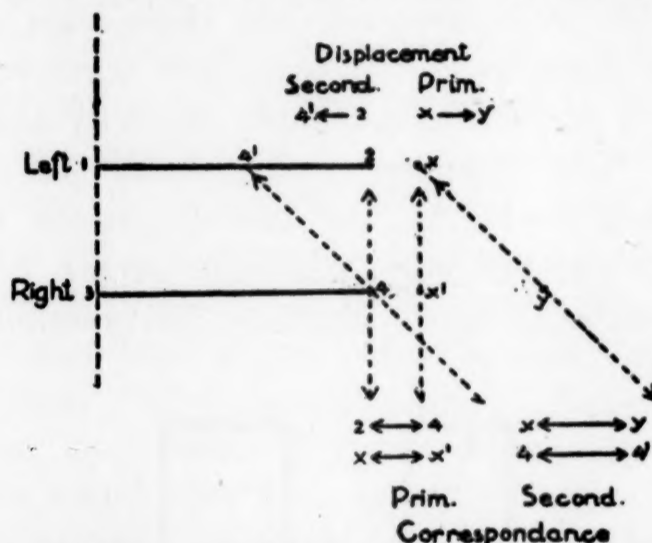of fixation (a secondary correspondence), the point *x'* of the

FIG. 44a.   Diagram explaining change in zero-correspondence.

right eye will be disparate relative to *x* (secondary disparity).
Furthermore, *4* is then no longer correspondent with *2*, but
with *4'* (*x4'=y4*). Should *2* become united with *4*, then, on
account of the (secondary) zero-correspondence *4–4'*, the points
2–4 are disparate, and *2* will be (relative to *4–4'*) nasally dis-
placed. Under these conditions *x–y* must appear in the plane
of fixation, and *2–4* in front of the plane of fixation. This is
exactly what the observer sees. The following conclusions may
therefore be drawn from the diagram: The more exactly the
frame lies in the plane, the stronger the depth effect of the hori-
zontal lines. The more the frame is pulled out of the plane
because of its primary disparity, the more nearly will the hori-
zontal line appear in the plane. Some experienced observers
are able, because of this, to see the configuration in three ways.
They may see the frame in the frontal parallel plane with the
horizontal line turned strongly out of the plane. Again, the

frame may have a distinct depth, and the horizontal line will be almost in the plane. Last, they may see the frame and the horizontal line both moved out of the plane of fixation, both pointing in opposite directions.

There are some pertinent questions which must be asked. Why do the horizontal lines not usually appear in the plane and the frame at an angle, according to a " natural " correspondence and a " natural " disparity? Why is the paradoxical phenomenon of the diagonal line and the frontally parallel frame the more commonly observed? The answer to these questions depends, obviously, on the difference in the stability of the two configurations. The frame is the more stable figure; the hori-
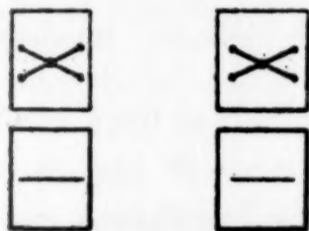

Fig. 45. Demonstrates the relation between displacement and figure-stability.

zontal, the more labile. Whenever there occurs a displacement process, it will effect the more labile, more fluid configuration the quicker. This may be demonstrated. If the middle figure is deliberately made the more stable, in that a cross-like form is substituted for the horizontal line, the depth effect of the middle figure will—for most of the observers—decrease. By the introduction of a second horizontal line the difference in the depth effect can be made a subject of comparison.

The lower line, which is less stable, moves away at an angle, for most observers, while the cross turns less. (Of course, the images must not be fixed too long, for as we have previously remarked, the lines may gradually fall back into the plane upon continued fixation.)

(c) *The concept of " relative " correspondence and " relative " disparity:*

If one speaks of primary and of secondary correspondence and of a primary and secondary disparity, it is implied that within a

specific field there are dynamic relations, which are expressed by a specific correspondence. Such a field need not comprehend the whole binocular range. It may be a smaller field, characterized by the one or another kind of correspondence. In other words, correspondence, in any given situation, is not absolute, but relative. Secondary disparity means a disparity relative to the zero-correspondence of the momentarily effective, specific field. The figure given below illustrates this fact:

FIG. 46. Stereoscopic pictures demonstrating the effect of " relative " disparity.

In this figure, the horizontal lines are all equal. Generally, in binocular unification, the lower line is seen diagonally with the left side forward. This line has a secondary disparity within the field proper to it, that is, the field which is inclosed by the thick lines. The " relative field " of the upper horizontal lines is the outer frame. In this field there is another secondary zero-correspondence which is a governing factor, for the primary disparity of the outer frame is opposed to the primary disparity of the inner frame. Because of this, the upper horizontal line appears most often in a somewhat diagonal position which is opposed in direction to the diagonal of the lower horizontal line. In any case, the lower line can be brought into relation with the outer frame by an intentional visual attitude on the part of the observer. In such an event, the depth effect just mentioned will decrease and eventually vanish, *i.e.*, the horizontal lines gradually approach the plane of fixation. Sometimes the horizontal lines may even undergo a reversal of depth effect. It may be said, in general, as this example goes to prove, that the field which most nearly closes the given figure is the field to which it is dynamically related.

The field to which the figure is related, it must be added, need not be one that entirely surrounds the figure. It suffices that the more stable form be arranged in such a way that the more

FIG. 47.   Secondary disparity outside of related field.

labile figure can be brought into immediate relation with it.   In Fig. 47 the stable form is a solid square, and the labile form a pair of points.   The square has a primary disparity, but, as a result of its stability, appears more or less completely in the plane of fixation.   The pair of points, which is characterized by a primary correspondence, may exhibit a secondary displacement. In this case, the right point appears to lie more or less in front of the left.   This paradoxical effect becomes all the more clear, the more the solid square lies in the plane of fixation.   The effect decreases, depending on the extent to which the square is pulled out of the frontal-parallel plane in accordance with its primary disparity.

(3) *Coöperation and counteraction in binocular displacement. The problem of binocular depth contrast:*

Our previous investigations have shown that zero-correspondence is not a constant relation, but is the resultant effect of primary ("geometrical-anatomical") factors and the factors of "configuration".   From the theoretical standpoint, the "geometrical-anatomical" conditions are more effective, the less the special effects proceed out of the configuration itself.   Should, for example, a certain disparate pattern have a strong resistance to change (*e.g.,* the frame figure shown above) the "geometrical" and "configurative" factors will offer each other a mutual opposition.   Suppose that there is a disparate frame figure which has the line *b* larger than the line *a* (Fig. 47a).   The zero-correspondence in this case is not merely dependent on the retinal geometry of the figure, but also depends on other properties.   If *1* and *3* are in focus, the unification of *2* and *4* brings
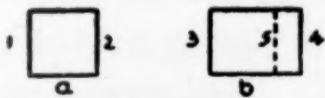

FIG. 47a.   Frame-figure which may explain change in actual correspondence.

the following possibilities: First, *2* and *4* show a minimum depth; the figure is completely in the plane. Second, *2* and *4* have a maximum depth, and the figure is diagonally placed. Third, *2* and *4*, with respect to *1* and *3*, have a depth which lies anywhere between the maximum and the minimum. If the geometrical-anatomical factor alone were the governing element, then there would be a zero-correspondence between the lines *2* and *5*, *4* would appear geometrically disparate with respect to *2–5*, and the whole figure would have a maximum diagonal situation. If, on the other hand, the factor of stability of configuration were the governing element, there would be a secondary zero-correspondence between the points *2* and *4*, *2* and *5* would be characterized by secondary disparity, and the figure would appear altogether in the plane of fixation. Since, generally speaking, neither the anatomical-geometrical, nor the figural, properties, absolutely dominate in such a pattern, the point *2* will have its zero-correspondent point somewhere between *4* and *5*. The nearer to *5*, the more diagonal and pulled out of the plane the figure will be. The nearer to *4*, the nearer does the figure approach the plane of fixation.

The concept of zero-correspondence is a convenient expression for the descriptive analysis of those phenomena which come under the category of "binocular depth contrast". The phenomena of contrast can be studied in Fig. 44. One can say that the frame figure induces a depth in the lines which is in contrast to the primary depth of the frame. This, of course, is merely a description of what is actually seen. A more precise insight into the nature of depth contrast may be gained from the theoretical discussion which is found immediately above. In the light of this discussion, the depth contrast is the direct result of the fact that the depth effect is dependent both on the geometrical-anatomical conditions and the stability of the figure (*i.e.*, of the frame). The stronger the figural property of stability participates in the determination of the depth effect, the greater the contrast induction which the figure brings to bear on the situation. Or, in terms of zero-correspondence, the greater the difference between the momentary zero-correspondence, and the

primary correspondence, the stronger will be the contrast effect. Let us turn once more to the diagram of Fig. 47a. The more the correspondence between *2–5* shifts in the direction of *2–4,* the higher the contrast effect in the field.

It is possible to have such a configuration that one can determine the points which stand in zero-correspondence, *i.e.,* according to the definition, the points which are binocularly unified and which appear in the plane of fixation.

The zero-correspondence for point *7* will be somewhere between *5* and *4.* (Fig. 48, A.) (The focal point is in the center of the figure.) Because of this, it is only necessary to shift *5* in the direction of *4* until *7–5* lie in the plane of the focus. The zero-correspondence for point *8* (somewhere between *6* and *3*), can be determined in the same way.

The lines in the field which are capable of producing a contrast need not be horizontal. They can also lie in a diagonal position. (Fig. 48, B.) In this latter case the depth effect would, no doubt, be less clearly defined, but it would be still present for the majority of the observers. After unification the right end of the line is seen in front of, and the left end behind, the plane. The zero-correspondence of the lines may be determined by tipping one line about its center until the unified image coincides with the plane of fixation.
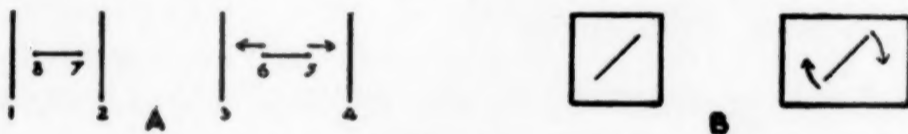

FIG. 48.   Patterns demonstrating how actual zero-correspondence could be determined.

Up to this point the problem of contrast induction has been demonstrated with configurations so constructed that the one figure (*i.e.,* the frame) has a primary disparity, and the other figure (*i.e.,* the horizontal lines) a primary correspondence. But this is a more or less abstract case. Cases where both figures have a disparity would approach nearer to the conditions of ordinary vision. Under such conditions, the contrast effect and the geometrical disparity could work either against, or with, one another. Some of these cases may be discussed here. For many observers, Fig. 49, *A,* despite its disparity, appears almost without depth. The untrained observer especially (that is, the observer who perceives more often according to figural than in terms of geometrical-anatomical correspondence) will almost never see the horizontal line turned out of the plane. In Fig. *B* two lower lines are so arranged that their cross-disparity is opposed to that of the upper lines. Each binocular line will now appear in contrast to the other line in such a way that it is

$$\overline{a_1} \quad \overline{a_2} \qquad \frac{a_1}{b_1} \quad \frac{a_2}{b_2}$$

Left   Right   Left   Right
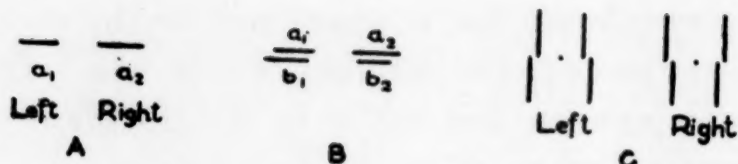
A   B   C

FIG. 49. Stereoscopic patterns demonstrating coöperative dynamics.

opposed to its localization in space. The contrast effect of the lower line works together with the natural disparity of the upper line, being opposed to the stability tendencies of the same line. Therefore the tendency to see the figure according to its natural disparity will be strengthened. The result is a heightening of the natural depth effect of the upper line. Analogously the depth of the upper lines in pattern C is strengthened by the lower lines.

An analysis of such an effect can be easily made with the help of the scheme Fig. 50.

The zero-correspondence in each pattern is dependent on three factors, on three "tendencies":

Symbol →1.—Geometry of the retina: zero-correspondence tends towards primary correspondence.

Symbol →»2.—Stability of the figure: zero-correspondence tends towards the points of congruence in the figure (secondary correspondence).

Symbol →»»3.—Contrast effect: zero-correspondence tends towards the points of congruence in the opposite figure.

In keeping with the stability factor of the binocular line $f1–f3$, the zero-correspondence of 1 will tend towards 3. It naturally follows that the observers will see, at the beginning, the straight line in the frontal-parallel plane. In contrast to this, there is the tendency, in keeping with the primary correspondence, to see not 3, but $1'$, as the corresponding point for 1. Already we note that there are two opposed tendencies seeking to determine the
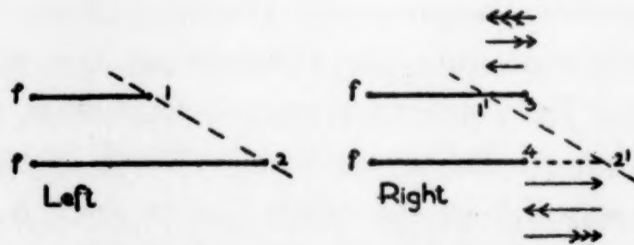
FIG. 50. Schema of coöperative dynamics.

zero-correspondence for point *1*. There is a $3 \leftarrow 1^1$ tendency, which is dependent on the " geometry " factor, and a $1^1 \rightarrow\rightarrow 3$ tendency, dependent on the stability factor. But this upper line is also dynamically linked with the lower line. This means that the lower line will exert a contrast effect upon the upper line as a result of its own stability tendencies. The stability tendency of the lower line is, naturally, at the same time opposed to its own " geometrical " factor. From the standpoint of " geometry ", the point corresponding to *2* would be *2'*, and from the standpoint of stability, it would be *4*. Because of this, the geometrical tendency to establish the zero-correspondence goes from *4* to *2'* ($\rightarrow$). The stability tendency, on the other hand, attempts to draw the point of zero-correspondence from *2'* to *4* in the direction $\leftarrow\leftarrow$. It is this last tendency which is carried over to the upper part of the binocular field, and which appears as the contrast effect ($\leftarrow\leftarrow\leftarrow$). It can be seen from the arrangement of the arrows that, in the upper line, the tendency to natural correspondence works together with the contrast tendency of the lower line, both together against the tendency to stabilization. The result of this is an increase in the " natural " depth effect.

The dynamism of the lower line can be determined in a similar way. Here, too, it tends to be expressed in geometrical, disparate depth.

If, therefore, the lower lines of Fig. 49, *B,* are covered, the upper one appears with very little depth to most observers. Some observers are unable to see any depth at all in the upper line if it stands alone.

Just as the contrast effect can support primary correspondence and disparity, so, too, it can work *against* them. The following stereoscopic figure may illustrate this (Fig. 51) :

FIG. 51. Stereoscopic patterns demonstrating counteractive dynamics.

The outer lines *b, c,* have a contrast effect on the inner, centrally located line *a.* This contrast, however, tends to oppose the primary disparity in line *a.* In accordance with the primary disparity, the line *a* must appear with the left end forward and the right end back. The contrast effect which proceeds from

the lines *c* and *b*, tends to turn *a* (secondary disparity) in such a way that the left end of the line is backward, the right end forward. This weakens the primary depth effect in the line *a*, or paralyzes it, or may even force the line in the opposite direction. The following diagram (Fig. 52) illustrates these possibilities:
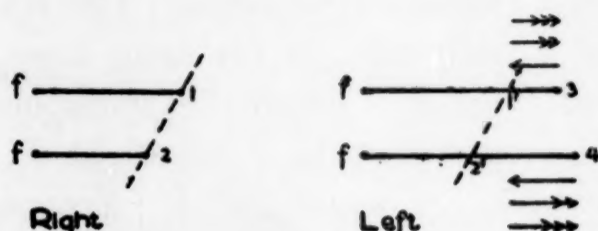

FIG. 52.   Schema of counteractive dynamics.

The zero-correspondence for point *1* is in *1'*, depending on the " geometry " factor.   It is in point *3,* if dependent on the stability factor.   The two tendencies to establish the zero-correspondence of point *1* in the right eye are *1'←3* (geometrical tendency), and *1'→→3* (stability tendency).   In the lower line, the stability tendency works to establish the zero-correspondence for *2* in point 4 symbolized by *2'→→4* (as opposed to the " geometrical " tendency, *2'←4*).   When it is transferred to the upper field, the stability tendency (*2'→→4*) becomes a contrast *tendency* (*→→→*).   In the upper line, the tendencies work in such a way that stability and contrast combined counteract the " geometrical " factor.   The result of this opposition is a weakening of the geometrical disparity.   Under certain circumstances, the contrast effect can become so great that it evokes a depth effect that is opposed to the geometrical disparity.

" Coöperative dynamics " and " counteractive dynamics " as a result of the coöperative effect or mutual opposition can be clearly demonstrated in the examples which we shall now discuss. If the following figure 53 is presented stereoscopically, and first the upper, and then the lower, circles are covered, this is what happens:

FIG. 53.   Counteractive and coöperative dynamics effective
in the middle line.

If the upper circles are covered, the central line will be seen approximately in the plane as the result of the counteraction on the part of the lower circles. If the lower circles are covered, the central line, in contrast to the upper circles, will appear turned out of the plane, because of a coöperative effect, which heightens the natural disparity of this line.

In the following instances these dynamics appear with particular clarity (Fig. 54). The figures are so constructed that the horizontal lines exercise a contrast effect on the vertical lines. In case I this contrast effect is active in a direction that tends to negate the "geometrical" disparity of the vertical lines. In case II, on the other hand, the contrast effect, proceeding out of
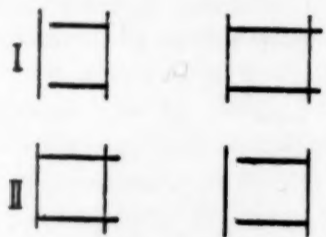
Fig. 54. Stereoscopic patterns showing counteractive (I) and coöperative (II) dynamics.

the horizontal lines, works together with the natural disparity of the vertical lines. The result of this is, that in case I the vertical lines approach the plane and, under certain circumstances, even exhibit a paradoxical depth, while in case II the depth of the vertical lines corresponds closely to what one would expect of the primary disparity, and is clearly and directly developed. It is to be plainly seen that the coöperative and counteractive effects depend on the stability of the horizontal lines. The more the horizontal lines are out of the plane, the less effective they are. This follows the theoretical results already gained and needs no further explanation.

Coöperative and counteractive dynamics may be demonstrated in these tilted figures (Fig. 55). The stereoscopic images I and II are equal insofar as the long tilted lines in both cases are geometrically disparate to an equal extent; therefore, in keeping with this fact, the same depth should be revealed in both cases. Actually, however, the binocularly unified short cross lines have

a contrast effect on the long lines, which supports the primary disparity in case I, and works against it in case II. The result of this phenomenon is that, in case I, the depth effect in the long lines is very strong, while in case II it is small, or there may be no depth effect at all, or one that is inverted.

FIG. 55. Stereoscopic patterns demonstrating coöperative (I) and counteractive (II) dynamics.

Two comments: (1) E. Lau [33], in his interesting investigations of the relation between the geometrical-optical illusions and binocular effect, came across a figural combination which is similar to the one given in Fig. 55. He used the Zöllner pattern (*i.e.*, parallel lines, which are crossed by other small lines) in his stereoscopic experiments. The only difference between the two half-images is that in one half-image the cross lines are more inclined to the parallel lines than in the other. Lau perceived a binocular depth effect in the parallel lines despite the lack of a primary disparity. From this he draws the conclusion that the binocular effect of depth is, in this case, occasioned by a displacement that is purely monocular in each eye, and is in accordance with the laws of geometrical-optical illusions. Since the lines are no longer parallel, but are seen in intersecting directions, there is a disparity present which is effective in each single eye before the binocular interaction takes place. On the basis of the phenomena as they are here presented, such a conclusion is untenable. The effect observed by Lau has no direct connection with any geometrical-optical illusion. It belongs, rather, to the same category as certain experiments which we have carried out. It is an effect that is directly dependent on a dynamic that is binocular, and not monocular. It is, precisely, a binocular contrast dynamic. That Lau's conclusions are unjustified will be demonstrated in the following discussions.

(a) Geometrical-optical illusions which do not develop a contrast dynamic, also do not exhibit any special effects. If, for example, the half-images of Fig. 56 (A) are stereoscopically united, the middle point of each line will indeed appear to be monocularly displaced in an opposed direction, but there is no depth effect. (b) In Fig. 56 (B) the vertical lines 1 and 2 appear to be bent by the cross lines (Hering's illusion).

Both images are bent in the same direction. If the two half-images 1 and 2 are united, the long lines appear to yield a concave depth effect despite their objective parallelism. If this effect depended on a monocularly developed disparity, conditioned by illusion, it would be expected that a unification of

[33] Untersuchungen über das stereoskopische Sehen, *Psych. Forsch.*, Vol. 2, 1922.
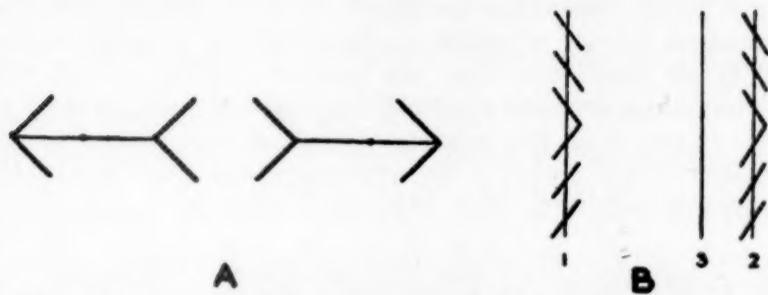
FIG. 56. Patterns which disprove a relation between illusion and depth effect.

lines *1* and *3* would show a stronger effect than the union of *1* and *2*. It is obvious that the straight line *3* differs more from line *1*, which has been bent by the illusion, and is therefore more disparate with respect to line *1*, than does line *2*. If the depth effect *1–2* is compared with the depth effect *1–3*, all observers report that there is a stronger depth effect in *1–2* than there is in *1–3*. Some observers, as a matter of fact, see no depth effect at all in the *1–3* combination. If the monocular illusion were actually the basis of the depth effect, it is just the opposite that we should have to anticipate. The fact that in combination *1–3* the depth effect often does not vanish again has nothing directly to do with an illusion. Such a figure may be reduced to the Wheatstone-Panum pattern (Fig. 57) in which two intersecting lines are presented to the one eye, and a straight line presented to the other. This

FIG. 57. Wheatstone pattern.

simply means that in this case the depth effect rests on a binocular dynamic, that is, on the binocular double relation of the single straight line to both intersecting lines.

(2) It is probable that the fact of binocular coöperative and counteractive dynamics can explain many problems which are centered about the concept of the "*horopter*". Since the empiric horopter is usually determined experimentally by linear configurations, it must follow that the figural stability tendencies of the thread-figures have an influence on the configuration of the horopter (horopter deviation, depth sensibility, etc.). Out of many problems, only the problem of the so-called "covariance phenomenon" (Jaensch) may be mentioned. If we hang three threads next to one another in such a way that they appear to lie in the plane of fixation, and then displace thread *1* a little forward or backward, thread *3* will also appear to be displaced with respect to the middle thread, and in the same direction as thread *1*.
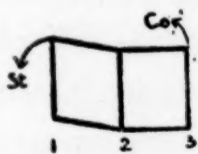

FIG. 58. Hypothetical explanation of "covariance".
St= figure stability; Co=contrast effect.

It is highly probable that the covariance we have just described can be given adequate explanation on the grounds of the contrast dynamic occasioned by the stability tendency of that plane that has been moved out of the frontal parallel position. The covariance phenomenon, then, can be considered as a special case of the dynamic tendency to displace the zero-correspondence, a tendency which is always present when stability of configuration and geometrical disparity work against each other.

(4) *The measurement of binocular depth contrast:*

Depth contrast must be measured in order to establish its existence beyond any reasonable doubt. The measurement can be made by using any one of the patterns in which the contrast effect is clearly apparent. The configuration which we have employed actually shows less of a contrast effect than, for example, the effect found in the pattern of Fig. 55, but we have chosen it because, in this particular pattern, all other possible interpretations except that of contrast effect seem to be precluded.

a b c   d e f   a' b' c'   d' e' f'

Fig. 59. Standard pattern used for measuring contrast.

In the unification of the six lines, left and right, the outer lines of each triple combination are seen to be tilted out of the plane.

The united middle lines—formed of " anatomically " corresponding lines—are thrown into contrast with the outer lines, and are, accordingly, tipped out of the plane in opposite directions. The middle line *e*, in keeping with this displacement, is in a position where it runs from above and forward to below and backward. The line *b* runs from a backward position above to a forward position below. The extent of the contrast is variable, as will be shown, and also varies for different individuals. If the observers, using a simple stereoscope, unite those patterns, the following differences have been found. Some subjects are inclined to see the middle lines moving in strongly opposed directions. Most of the observers, however, see them only slightly tipped away from each other. Finally, some of the observers see them practically in the plane. In this last case as it is shown by the use of a " contrast stereoscope " there is nevertheless evidence of a depth effect, but it is so small that it must be measured in order to determine it.

The principle involved in the measurement of the contrast effect is the following (Fig. 60): The middle line of the right half-image, b', is turned about its center in a clockwise direction. This action occasions in $b–b'$ an objective, binocular depth, which is working counter to the contrast effect. By means of such a movement, the contrast induction can be counterbalanced. The turning movement must be continued until the unified middle line appears in the frontal-parallel plane. The more b' has to be turned ($\angle\beta$), the stronger has been the contrast brought about by the outer lines. Or, in terms of zero-correspondence, since the outer lines, as a result of stability tendencies, displace the zero-correspondence, there is now the task of determining the zero-correspondence present in the figural field. The contrast

FIG. 60. The figure shows the principle of contrast measurement.

effect is then equal to the difference (β) between the primary and the actual zero-correspondence.

The stereoscopic apparatus, which shall presently be described more precisely, is based on the principle of measurement just elucidated. The stereoscopic pattern used is the three thread pattern of Fig. 60. The observer looks through the stereoscope at a white double frame, behind which there are hung 3 thin black threads (diameter .004 in.) for each eye against a white background. The mechanism of this apparatus (see the description) permits, first, a symmetrical variation of the distance of the outer threads left and right with respect to the middle thread; and, second, a simultaneous rotation of the outer threads of the left triple combination, $a–c$, so that they move as far as a maximum of 25° about their centers; and, last of all, a rotation of b resp. b' about their centers in the plane. In each single observation, b' is that thread which is turned about the center until $b–b'$ appear to be in the frontal parallel plane. The value of the angle of rotation of b' is read off a scale at the back of the apparatus in minutes and degrees.
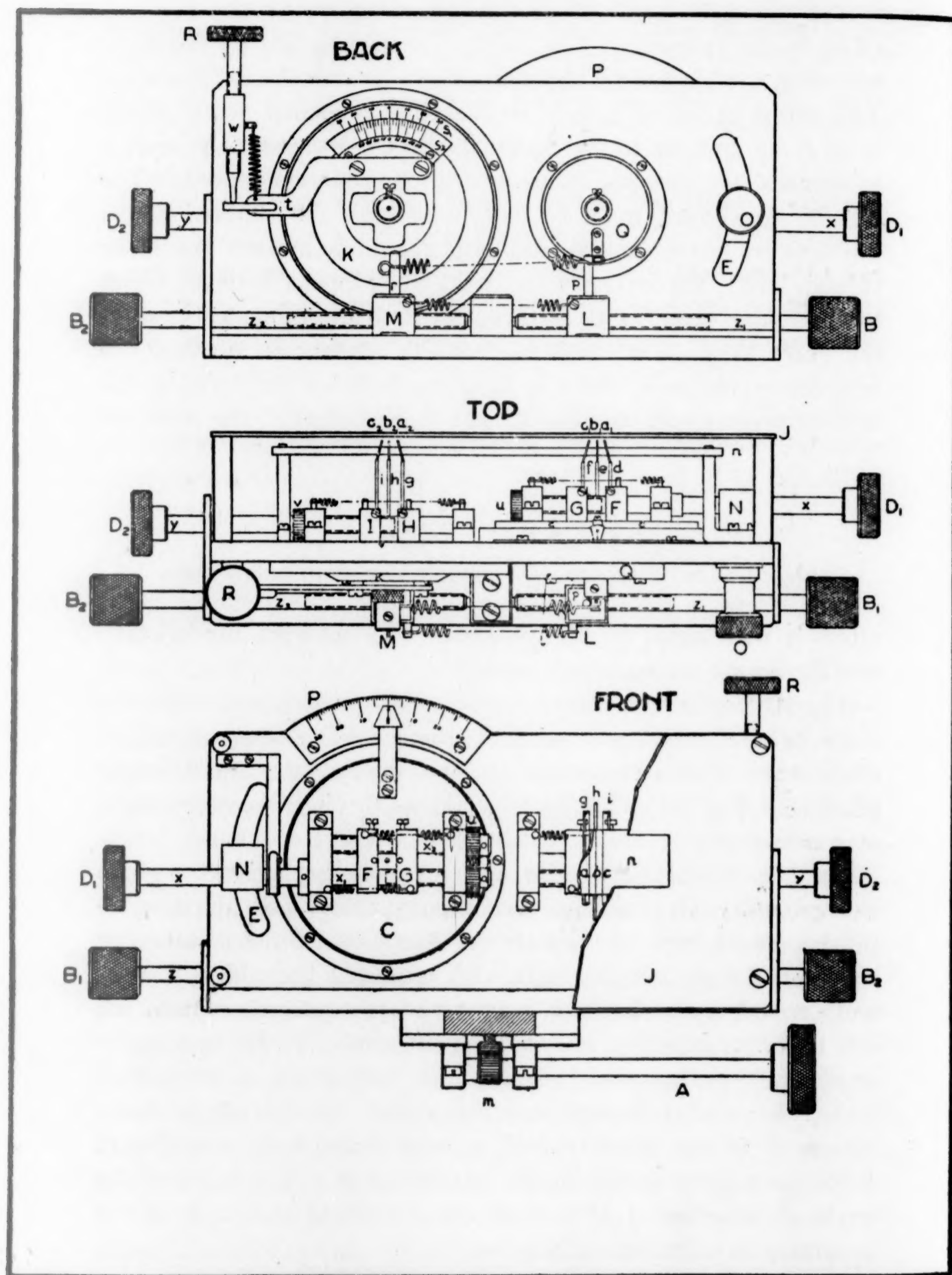
FIG. 61. Contrast Stereoscope.

Explanation of Fig. 61 (Contrast Stereoscope)

The apparatus is set on a tripod. In front of it there is placed a Brewster stereoscope. At the top there is a metal box containing three 6-volt lamps.

a_1, b_1, c_1 and a_2, b_2, c_2 (vid. Fig. 60) are thin black wires (diameter .004 in.) which are fastened to the forks d, e, f, and g, h, i, respectively. The forks d and f (together with the threads a_1, c_1, can be rotated by turning the disk C. When the disk turns, a contrast effect appears in the center line b, which can be compensated by turning fork h (thread b_2); h is rotated by turning disk K.

A is the adjustment for changing the distance between the prisms and the threads. Apparatus is moved backwards and forwards by means of the gear m.

D_1, D_2, are adjustments for regulating the distance between the outer threads a_1, c_1 and a_2, c_2, respectively. By turning the screw D_1 (threaded rod x_1) the block G is moved in the horizontal direction; threaded rod x_2, which is connected to x_1 by the gear u, turns synchronously with x_1, and moves the block F in the opposite direction to G. This occasions a movement of the threads a_1, c_1 (forks f, d) towards, or away from, each other. A similar arrangement is provided for the movement of threads a_2, c_2 (forks i, g). These are set in motion by means of the threaded rods y_1, y_2, connected by the gear v to the to the blocks H, I.

B_1, B_2 are adjustments for rotating the center threads of b_1, b_2 (respectively forks e, h). The left center fork, e, is connected to the rear disk Q. Q—and therefore e—can be rotated by moving the block L (and peg p) along the threaded rod s. In a like manner, fork h is fastened to the right rear disk K, which is rotated by means of the threaded rod z_2, block M, and peg r. The amount of rotation of the right-hand disk K can be measured by means of the upper and lower scales S_1, S_2. The zero-position on the scale (*i.e.*, the position where the binocular thread b appears in a frontal-parallel position) can be adjusted by the rotation of the lower scale S_2. This can be accomplished by turning the screw R, the threaded rod w, and the lever t. (Lower scale is attached to t.)

Adjustment for rotating the left-hand threads a_1 and c_1: E is a slit along which the block N can be moved (by rotating the rod x). N will turn around the front disk C to which the blocks G and F (and the gear system x_1 and x_2) are attached. The rotation can be measured by the front scale P. The position of the disk can be regulated by the screw O.

J is a section of the white screen in front of the apparatus where there is an aperture for the left and right eyes. n is a milk-glass between the forks and threads which is illuminated from above by the 6-volt lamps.

Results of the experiments with the contrast stereoscope:

The results are collected together in 3 tables. *Explanation of the tables:* XV, XVI, XVII. The outer lines of the left half-image as seen through the contrast-stereoscope are varied by a movement which turns them about their centers. The angle $\angle a$ through which they turn (vid. Fig. 60) measured from the vertical to the left or right, has a value of $1°$–$7°$. The measurements in all cases refer only to movements which are counterclockwise. The values of clockwise movements have been computed, but since they are not materially different from those for

TABLE XV

SHOWING CONTRAST EFFECT IN LINE в (effect is measured by $\angle\beta$)

Constellation (constant): $\angle a = 5°$; d (distance $a_1 c_1 = a_2 c_2$) = 4 mm.; 10 O's.

O	I	II	III	IV	V
$\angle\beta$	5° 2.3′	4° 32.0′	2° 18.3′	1° 13.0′	1° 24.0′
	± 8.3′	± 11.8′	± 6.7′	± 8.6′	± 9.1′

O	VI	VII	VIII	IX *	X *
$\angle\beta$	1° 3.2′	0° 39.1′	0° 15.3′	1° 41.4′	1° 11′
	± 8.3′	± 5.5′	± 2.1′	± 49.3′	± 42.3′
				Range:	Range:
				0° 35′–3° 10′	0° 25′–2° 15′

* Wide range of variation in contrast effect.

counterclockwise movements, they were disregarded for the sake of simplicity. The second variation refers to the distance separating the outer lines from one another. The outer lines in both half-images are always an equal and variable distance apart. The distance separating these sets of outer lines varies from 4–10 mm. Table XV gives the average values for the contrast effect in a constant pattern. Distance of the outer lines *a* and *c* in both half-images d=4 mm. Angle of rotation of the outer lines in the left half-images $a = 5°$. There are 10 O's. All values are averages taken from 18 trials.

Table XVI represents the values of different constellations for 5 O's. Variation of $\angle a$: $1°$–$7°$. Each value is an average taken from 18 trials.

In both these tables the numbers represent the average and the average deviation of the angle of movement β (referring to the

TABLE XVI

SHOWING CONTRAST EFFECT ($\angle\beta$) UNDER VARIATION OF $\angle\alpha$

Constellation: $\alpha=1°$ to $7°$; $d=4$ mm. 5 O's.

O	$\alpha=1°$	$\alpha=2°$	$\alpha=3°$	$\alpha=4°$	$\alpha=5°$	$\alpha=6°$	$\alpha=7°$
I	1° 25.3′	1° 50.3′	2° 48.9′	3° 35.2′	5° 2.3′	5° 32.4′	6° 20.3′
	± 4.5′	± 7.2′	± 5.4′	± 9.7′	± 8.3′	±10.4′	±12.4′
II	1° 22.1′	1° 52.1′	2° 25.0′	3° 25.2′	4° 32.0′	5° 8.2′	5° 23.8′
	± 7.1′	± 6.8′	± 8.1′	± 9.2′	±11.8′	±10.3′	±15.3′
III	0° 25.4′	0° 55.2′	1° 26.1′	1° 51.8′	2° 18.3′	2° 36.4′	2° 45.0′
	± 5.6′	± 5.4′	± 5.2′	± 5.8′	± 6.7′	± 6.2′	± 7.8′
VI	0° 36.1′	0° 44.0′	0° 52.1′	0° 59.2′	1° 3.2′	1° 10.0′	1° 3.8′
	± 4.4′	± 5.3′	± 6.1′	± 4.9′	± 8.3′	± 7.8′	± 9.9′
VIII	0° 10.1′	0° 10.1′	0° 12.2′	0° 15.1′	0° 15.3′	0° 27.2′	0° 17.1′
	± 1.1′	± 1.5′	± 1.3′	± 1.9′	± 2.1′	± 2.3′	± 3.0′

middle line of the right half-image). β indicates just how much the line b', which stands in contrast, must be turned in order to bring bb' into the frontal-parallel plane. The extent of the angle is proportional to the contrast effect.

In table XVII are given the results of a variation of $d=5–10$ mm. These results are calculated in a form which reveals the percentual increase or decrease of the contrast effect relative to a standard constellation where $d=4$ mm.

TABLE XVII

SHOWING VARIATIONS OF CONTRAST EFFECT WITH VARYING DISTANCE
$d=5$ to 10 mm.

The variations are expressed in average deviation (percentage) from a contrast effect with $d=4$ mm. $+$ means percentage increase of β; $-$ means decrease of β.

O	mm.	$\alpha=1°$	$\alpha=2°$	$\alpha=3°$	$\alpha=4°$	$\alpha=5°$	$\alpha=6°$	$\alpha=7°$
S_I	5	+ 4.2	− 6.7	+ 5.8	+ 3.8	− 4.5	+ 1.9	− 0.9
	6	− 3.2	+ 3.9	− 3.9	− 6.5	− 3.5	− 3.5	− 2.3
	7	−10.3	− 6.3	+ 5.8	− 4.3	+ 2.6	− 9.8	+ 1.1
	8	+ 6.1	− 9.4	−10.2	− 8.9	− 8.8	− 6.3	− 5.8
	9	− 7.2	− 7.4	−10.4	− 7.8	−10.6	− 9.9	− 7.2
	10	− 8.4	−12.3	−13.3	−10.3	− 9.3	−10.3	− 3.3
S_{II}	5	+ 1.2	− 1.3	+ 2.5	+ 5.9	+10.6	+ 1.3	+ 4.3
	6	− 2.8	− 3.2	− 1.8	+ 5.8	+ 3.3	+ 2.8	+ 3.8
	7	+ 4.3	+ 0.9	− 1.3	+ 6.3	+ 5.7	+ 3.1	+ 2.8
	8	+ 6.2	+ 4.3	+ 5.8	+ 5.9	+ 5.8	+10.3	+ 5.3
	9	+ 6.1	+ 3.9	+ 8.8	+10.3	+ 8.3	+10.9	+ 5.9
	10	+ 3.8	+ 8.3	+10.3	+10.7	+12.1	+ 7.8	+ 6.3
S_{III}	5	+ 3.3	− 5.4	+ 3.5	+ 4.8	− 3.6	+ 0.2	− 1.8
	6	− 4.3	+ 0.9	− 5.9	−10.3	−10.1	− 5.3	− 4.4
	7	+ 5.7	− 6.2	− 9.5	− 5.7	+ 0.8	− 6.4	− 4.1
	8	+ 3.8	− 8.7	− 7.9	− 6.2	+ 5.7	− 6.1	+ 3.3
	9	− 6.7	−11.4	− 5.7	− 8.3	− 8.2	− 4.1	− 9.8
	10	− 4.9	− 7.5	− 7.4	− 7.6	− 6.8	− 2.3	−10.2

Summary and theoretical discussion of the experiments with the contrast stereoscope:

(1) The contrast influence of the outer lines on the middle lines is reported by all (10) O's without exception.

(2) The value reported for the contrast effect varies greatly among all the O's. When, for example, a constellation is used in which $a=5°$, $d=4$ mm., β equals $5° 2'$ for one observer, and $0° 15'$ for another. These were the extremes between which lay all the other values reported by the rest of the O's.

(3) The absolute value of the contrast effect rises, in general, with the increase in the angle of rotation a, *i.e.,* with an increase in the disparity of the outer lines.

(4) Within the distance d as we have limited it in these experiments, the angle of rotation a of the left outer lines is the only objective factor which clearly modifies the value of the contrast effect. Within the variations which we have used here, there is no indication that the distance d of the outer lines exerts an unequivocal influence on the value of the contrast effect.

(5) It is theoretically important to take note of the report of the majority of observers that the contrast effect varies during the observation, and that it decreases or increases, depending, in a reversed relation, on an increase or decrease in the depth of the outer lines. At the beginning of each single observation, the contrast effect appears generally to be more pronounced than it does as the observation continues. The values which we have set down in the tables are taken at the end of each single observation.

The results of this series of experiments fit in completely with the theory of depth contrast. Contrast appears in the perception as soon as the configuration which governs the binocular field possesses a stability which will shift the primary zero-correspondence within the field. The contrast effect lies between a maximum and a minimum of stability in the frame-like figure. If there is a maximum of figural stability, that is, if the frame is seen in the zero plane, then the extent to which the zero-correspondence shifts within this field is maximum. Or, what is precisely the same, the contrast effect is at a maximum. If the

figural stability is at a minimum, the configuration will be seen at a maximum depth, the zero-correspondence coincides with the primary correspondence, and the contrast is at a minimum. The observers corroborate these statements. The strength of the depth of the frame figure and the contrast effect are inversely proportional. It follows in line with the general theory that the contrast value rises with the angle of rotation of the (left) outer lines. The zero-correspondence, naturally, has a wider range of displacement with an absolute increase in the primary disparity.

The fact that all the observers employed in these experiments report the perception of a contrast effect, indicates that the tendency to stabilization, which proceeds from the outer figure, is usually present in the binocular perception. It is theoretically quite tenable that the stabilization tendency for certain observers may have the value of 0. In such a perception, the outer figure would have its maximum depth value. The depth perception of such observers would follow completely the primary retinal correspondence and disparity. At the same time a contrast effect would be entirely lacking. It may be assumed that such an extreme retinal perception occurs rarely, if ever.

APPENDIX

Tentative Hypothesis of Depth

Up to this point the theoretical discussions, and the conclusions arrived at, have been exclusively concerned with the analysis of phenomena which appear in depth perceptions. There was no deliberate intention, in these experiments, of explaining depth itself. This problem, however, shall not be relinquished without an attempt to present some sort of hypothesis seeking to bring to light the psycho-physiological nature of the phenomenon of depth. This hypothesis should be considered merely as a tentative interpretation the truth in which will be dependent on further illuminating experiments.

First Section of Hypothesis:

Any serious theory of binocular depth perception is necessarily based on the fact that binocular depth occurs when the primary correspondence of the retinas is disturbed by the presence of a configuration which forces some sort of change in the " natural " correspondence. The perceptual facts of correspondence—disparity and displacement—are the bases on which any hypothesis must stand.

I do not believe it possible that the phenomenon of depth can be explained by anything but " depth " itself. Such words sound paradoxical indeed, but it is just this premise which gives Hering's theory of depth the logical advantage over hypotheses such as that of Jaensch,[34] for whom the decisive depth factor is the " visual attention "; of Tschermak,[35] with his " muscular tension-patterns "; and of Lewin-Sakuma,[36] who assume

[34] Über die Wahrnehmung des Raumes, *Zsch. f. Psychol.*, Suppl. VI, 1911.
[35] Über die Grundlagen der optischen Lokalization nach Höhe und Breite. *Ergebn. d. Physiol.*, IV, Abt. 2, 1905, 559.
[36] The work of Sakuma and Lewin (Die Sehrichtung monokularer und binokular Objekte bei Bewegung und das Zustandekommen des Tiefeneffektes, *Psychol. Forschung,* 6, 1925) is otherwise, in its general dynamic

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" stresses " and " tensions " in the binocular field as a correlate of depth.

It is known that E. Hering's depth hypothesis is based on the idea of depth values which are intrinsically situated in the retina. But, as our own experiments and those of others give ample proof, there is a whole series of facts which Hering's hypothesis, although logically consistent, does not cover. Its fundamental weakness, as we have tried to demonstrate, is its geometrical and static character. It quite ignores the dynamic, process-like character of the binocular phenomenon of depth.

If an hypothesis of depth is to have a dynamic character, it is quite possible to demonstrate the problem by the phenomenon of depth movement, which can be observed with relative facility by the use of the strobostereoscope. It may be said that the movement, either backward or forward, is linked psycho-physiologically with a side-wise movement. This is certainly true insofar as they are both " movements ". It is, therefore, plausible enough to assume that the psycho-physiological process that underlies the depth movement and that which underlies the side-wise movement are the same type of process. Pure depth movement of a point may be defined from the psychological standpoint as a movement in which the width value of the point remains constant. Pure depth movement is, so as to speak, " movement at a place of a constant width-value " (that is, in case " width " is determined by the distance of the point from the focus). The general psycho-physiological process which refers to any form of visual movement is, in a larger sense, a process which is chiefly characterized not merely by a change in width values, but more generally by a " direction ". A change in width is a special case of the general fact of a phenomenon which has direction. Movement processes of any kind are perceptual processes which have the spatial characteristic of " direction ".

Furthermore, we have previously shown that depth occurs

aspect, very close to our own.—K. Koffka, speaking of " stresses " and of " dynamic forces " in the binocular field, emphasizes the reservation that he intends no explanation of depth to be drawn from these words. V. his inspiring article " Some problems of space perception ", *Psychologies of 1930* (Murchison), p. 181.

during a process in which both the half-images change their width-values in a certain direction. Depth is produced not through any unification of the half-images, but rather through the process that leads to unification. The depth phenomenon must, therefore, be related to this process of unification. The change in place values during the unification can be considered as identical with a movement, and, indeed, with a movement in the width.

The first part of the depth hypothesis must read something like this: The stereoscopic phenomenon develops within the process (of movement) during unification, for it is only this process of unification that is capable of producing binocular depth. Since depth-movement, according to our definition, is a " movement at a constant width value ", the unification itself, however, takes place as a width movement; it must follow, then, that depth can arise only from a transformation, within the process, of width movement into movement at a place of a constant width value. This first part of the depth hypothesis seems to me to be of logical necessity, regardless of the relative truth or falsehood of the second part of the hypothesis.

Second Section of Hypothesis:

The second—and more speculative—part of the hypothesis is concerned with the question of how such a transformation of one kind of movement into another kind shall be conceived. Let it be given that *a* and *b* are the two disparate half-images in the binocular field which are involved in a process of unification. The disparate half-image *b* is a stimulus for the change in the position of the half-image *a*. Or, what is just the same, for the movement of *a* in the binocular field in the direction of *b*. The stimulus *b* determines the process of movement of *a* so far as direction and energy are concerned. If *b* is near *a*, less energy is necessary than when *b* is farther removed from *a*, in order to introduce a successful process of unification with respect to *a*. While the unification process, effective for *a* in the direction of *b*, is in a stage of development (as determined by direction and energy), *b*, affected by the stimulus of *a*, suffers a simultaneous

change of width values. The process of movement which proceeds out of *a*, as determined by the original place values of *b*, will, accordingly, reach the goal of unification with *b* before its full potentiality has been exhausted. Suppose it were assumed that this process were characterized by the energy γ. This movement process, γ, would not be exhausted when *a* was finally united with *b*. For a certain period it would continue to exert itself in the same width position. The continuation of the process of movement at a constant width value is, logically, *depth movement*. What applies for the process of movement γ of the point *a* also applies for the process of movement ψ of the point *b*. In other words, the mutual stimuli, on the one hand, and the premature attainment of the common goal on the other, may be conditions which govern the fact that *a* and *b*, partially at least, round out the movement in a common position, and for that reason continue in a depth-wise direction. A diagram to illustrate this idea might be constructed like this:
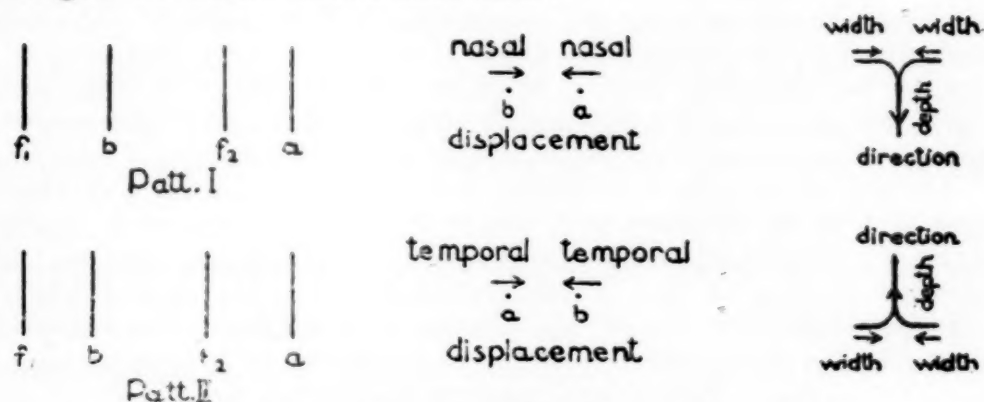

FIG. 62. Diagrams illustrating depth hypothesis.

The direction of the process of width movement should determine, naturally, the direction of the depth movement. If the unification is nasal in direction, then the depth movement should be opposed to the movement which would arise if the unification were temporal in direction.[37]

Three remarks: (1) The phenomenon which we have just represented is, of course, only a basic schema. One must imagine this process of transformation of width-movement into depth-movement as something that is recurring again and again during the whole period of unification. This must be true, for,

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[37] One must not assume, however, that this hypothesis has to be based, necessarily, upon visible movement. One could easily substitute the more general term of a "continuous change in space" for the concept of "movement".

according to our previous discussion (v. Part I of this monograph), *a*, before it is unified with *b*, is constantly uniting with the non-stimulated points of the other retina, as it moves nearer and nearer to *b*. Schematically represented:
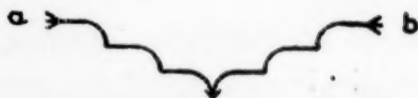

FIG. 63. Procedure of unification according to hypothesis.

This illustration also makes the depth effect in double images clearly understandable.

(2) The greater the displacement, the higher the (absolute) amount of width, which is subjected to transformation. It is a matter of indifference whether this increase in displacement is the direct result of increased geometrical disparity, or the result of the increased "velocity-parallax" of eye-movements.

(3) Such an hypothesis may finally lead to a theoretical interpretation which provide a satisfactory conciliation of *binocular and monocular depth perception*. Stroboscopically evoked monocular depth belongs, without doubt, to the strongest of all monocular depth phenomena, and in plasticity is almost equal to its binocular counterpart. If two figures of different size (Fig. 64, A), but of the same form, are presented successively in the stroboscope, either a distinct change (reduction or increase) of size may be perceived. Or it may be that the figure is seen moving backward (or forward); in this last case, however, the differences in size between the two figures will be reduced. Here, again, the condition which determines the appearance of the depth phenomenon is an identification of disparate figures (equalization of size). In this case the disparity is not binocular, but monocular. The points *1* and *2* are more or less identified with the points *3* and *4* according to the principle of " constancy of size ". All that we now have to assume is that the impulse for a displacement movement of *1* in the direction of *3*, and of *2* in the direction of *4*, follows the retinal stimulus conditions, while the perceptual displacement, governed by the laws of the constancy of size, is actually smaller. In the most extreme case of an absolute constancy of size, the process of movement, *1* in the direction of *3*, and *2* in the direction of *4*, would be perceived in a pure movement at constant width values. This is equivalent to saying that the movement process is seen as a complete depth movement. In all other instances, the less depth movement there is, the more width movement. A maximum width movement, which would correspond completely to the retinal displacement, would preclude any transformation of the one type of movement into the other, and therefore there would be no depth.

The principle of monocular depth movement (analogous to the principle of binocular depth movement) may therefore be stated as follows: During an actual movement, a perceptual decrease in the amplitude of the width movement ("displacement") occasions depth. This principle may help to under-
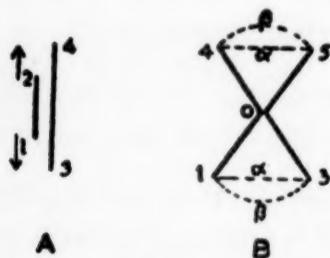

FIG. 64

stand the well-known stroboscopic figure (Fig. 64, B). When there is a succession of $\angle 1$–0–4 and $\angle 3$–0–5 in the stroboscope, there will be generally seen a movement of the angle, not in the plane, but, around a vertical axis, out in space. The path of movement is either behind or in front of the plane. If the lower part of the figure is covered, however, there is usually a two-dimensional movement of 0–4 in the direction of 0–5 in the plane. The retinal movement would, accordingly, be the circular movement β in the plane. Should the figure be seen completely, however, the angle, as a result of a tendency to remain constant, will retain its given form during the movement, or, what is exactly the same, the legs of the angle do not undergo any change in direction relative to each other. In the perceptual field, therefore, there will be a displacement which makes the path of movement α, and no longer β. The amplitude of the path of movement 4–5, respectively 1–3, appears to have diminished, and a depth follows. This depth is most striking at that point when the decrease in (two-dimensional) amplitude is greatest, that is, at a middle point between 4–5, 1–3, and reduces at either side.

It is possible that this tentative hypothesis may be of help in understanding the basic phenomenon of binocular depth. In the light of such an hypothesis, one may understand why depth depends not on displacement *per se,* but on the process which leads to displacement. It must be borne in mind that depth, as we understand it, is not conditioned by a transformation of the width-values of the retinal points (displacement) itself. It is rather conditioned by a transformation of a movement of a potentially longer width into a movement of an actually shorter width.

If points on both retinas are united in such a way that there is no process of displacement at all (primary correspondence), or if—after actual displacement—the images remain perfectly united and no further process occurs (secondary correspondence), there can indeed be no transformation of movement and, therefore, no depth.

One can now understand the apparent paradox that images seen only for a split second can exhibit depth, yet, in the continued projection of stereoscopic images, depth arises slowly out of a stage that is not at all tridimensional. In the first case, the process of displacement and the subsequent transformation of movement are given as a single, rapid, and non-repetitive process. During a continued observation, stability in the united images may very easily appear—providing, of course, the displacement is not too great—so that any process of displacement, and conse-

quently any transformation of movement, is precluded. It is only when this stability is overcome by subjective or objective factors that the conditions favorable to the appearance of depth are once again attained. These conditions, in general terms, are the " unrest " in the binocular field, pointed out by Karpinska. However small it may be, it suffices to evoke again the process of unification and, in consequence, the transformation of movement which gives rise to depth.

SUMMARY

I. *Experiments with half-images:*

Facts experimentally established:

1. A half-image, a_1 (joint half-image), that is seen together with another half-image, a_2, as a double image, has a space value in the binocular field which differs from the space value of the same image as seen in isolation. (It must be premised that the single observation does not last too long, approximately 1–2 sec.). The joint half-image, a_1, relative to its monocular space value, undergoes a displacement in the direction of the other half-image. On the other hand, the isolated half-image, a_1, is generally not displaced at all with respect to its monocular space value.

2. The relative value of the displacement is dependent on the objective disparity between the two images. After a certain degree of disparity, the relative displacement decreases as the disparity increases, until at last (assuming that there is a strict fixation of a certain length of time), the displacement approximates the value of 0.

3. Displacement is essentially increased by eye-movements.

4. When there is a movement of the objects, the displacement is essentially increased.

5. Displacement is fundamentally decreased by continued strict fixation.

6. Displacement and depth perception are closely linked. Generally speaking, binocular depth (providing that " empiric " factors neither obstruct nor augment the process) becomes sharper and greater with an increase in displacement, and more and more diminished with a decrease in displacement. The direction of the displacement runs parallel to the direction of the depth. Nasal displacement (no matter in which eye) runs parallel to a forward movement of the depth; temporal displacement runs parallel to a backward movement of the depth. So far as the isolated half-

image is concerned, there is a relatively negligible displacement, and the depth, accordingly, is that of the plane of fixation.

Theory:

1. The displacement of disparate half-images is the expression of a perfect or imperfect unification of the two half-images in the binocular field. The relation between displacement and depth is the same in the double image as in perfect unification. This indicates that both retinas coöperate as a binocular unity in the perception of double images. Displacement of the double image may be most easily understood by means of the hypothesis that disparate figures bring both retinas into such a congruence that stimulated points of the one retina come into functional relation with non-stimulated points (*i.e.*, disparate points) in the other retina. (See experiments with fragmentary and strobostereoscopic images.)

2. The increased depth effect and the higher displacement during movements of the eyes lead back to a velocity parallax between the successively fixed points (that is, to a difference between the speed of separation and the speed of unification . . . speed of separation is less than the speed of unification).

3. The decrease in depth and displacement during fixation can be *directly* accounted for by the diminution of the dynamic between the two half-images, and may also be *indirectly* accounted for by a decrease in the extent of eye-movements, and therefore a decrease in the velocity parallax.

4. The increase in displacement and depth during objective movement of an object which is seen in double images may be grounded directly on an increase of the dynamic relation existing between the half-images, and may also be grounded on an increase in the eye-movements, and consequently on an increase in the factor of velocity parallax.

II. *Experiments with Panum-pattern:*

Facts:

1. In the basic Panum-pattern the one half-image consists of two lines; the other, of one. If a binocular relation between both

half-images is established, both lines are displaced in directions opposed to each other.

2. Generally the direction and amount of the displacement determines the direction and amount of the depth effect. A nasal displacement causes a movement out of the plane and forward, a temporal displacement a movement backward.

3. If no displacement occurs the typical depth effect of the Panum-phenomenon is lacking.

4. If the displacement, by introducing particular configurations (dot pattern), is increased, the depth effect, too, is strengthened.

Theory:

The Panum-phenomenon is a special case of the dynamics of half-images. The simultaneous relation of c to a and b has been made visible by the use of the dot-pattern. The Panum-phenomenon is not the direct result of successive movements of convergence, although those movements may support the effect (velocity parallax); this again is demonstrated by the visible simultaneous unification of the one line with the double lines in directions opposing to each other (dot-pattern).

Moreover, in order to see the Panum effect, a perfect unification is not needed at all; the only necessary condition is that there exists a dynamic interaction between a–b and c which results in a displacement. In this particular case the theory leads back to the discussion of the depth effect in ordinary double images.

III. Strobostereoscopic experiments:

Facts:

1. If the Panum-pattern is strobostereoscopically presented, three phases are distinguishable as the speed of succession increases: I—Ambivalent depth movement; II—non-ambivalent, stereoscopically "correct" depth movement; III—flickering stage at a stereoscopically "correct" depth.

2. If the distance separating the double lines is increased, the different phases are transferred to higher zones of speed of succession.

3. The depth movement of the second phase, with respect to that of the first stage, is characterized (a) by an irreversibility of depth, and (b) by a displacement of the lines in the binocular field.

4. If the dot-pattern is substituted for the unbroken-line pattern, phase II is reached at a lower rate of succession.

Theory:

1. The depth movement of the first phase does not differ from a monocular stroboscopic depth movement. The depth movement of the second stage, on the other hand, is the result of a genuine, continuous, binocular process. The single successive half-images are continuously displaced as they are binocularly united with non-stimulated, steadily changing points in the other retina.

2. The binocular interaction between both retinas depends both on the objective space-parallax (expressed by the distance $a-b$) and on the " time-parallax " τ (the interval between the exposure of the two half-images.

3. If the dynamic relation of the two retinas is strengthened by some change in stimuli (substitution of the dot-pattern for the unbroken-line-pattern), the " correct " depth effect appears at a lower rate of succession.

4. The intensity of the relation of a point in the one retina to its counterpart in the other retina depends on the binocular dynamics of the whole configuration of which these two points are a part. (This is demonstrable by experiments with the stair-pattern.)

5. Experiments with patterns in which the half-images are differently formed (zig-zag pattern, bow-pattern) illustrate with particular clarity the fact that each half-image is displaced because of an interaction between itself and non-stimulated points in the other retina.

IV. *Stereoscopic and strobostereoscopic experiments with fragmentary images:*

Facts:

1. Fragmentary images are so constructed, that parts of the one half-image have no counterparts in the other eye. Such

images, if seen simultaneously and stereoscopically, may be characterized by a depth effect. If the depth effect is present, the fragmentary images appear to be displaced. The depth effect, in any case, is lessened with respect to perfect images.

2. Fragmentary half-images which are presented alternately by means of a strobostereoscope also show a displacement. To each eye, two sets of lines of different length are exposed in such a way that the long lines are in binocular focus, and the short ones present only in the upper part of the retina, for the one eye, and only in the lower part of the retina, for the other eye, with both on the same side of the field. The two short lines are at different distances from the focus. Should the half-images be given a successive exposition, a diagonal movement of the short lines is seen at a slow succession. At a higher speed of succession, the movement tends to run parallel to the focus-line. The distance separating the parallel movement from the focus-line is approximately the average between the distances separating the two short lines from the focus.

Theory:

The experiments with fragmentary images indicate that, because of the tendency to unite both half-images dynamically, there is a displacement of each half-image. This displacement is the expression of a binocular interaction, which leads to the result that each fragmentary half-image tends to coincide with disparate, objectively non-stimulated points in the other retina.

V. *Displacement and dynamic. Experiments in binocular depth contrast:*

Facts:

1. There are some cases in which, despite a unification of the disparate images, that is, in spite of objective displacement, there is no depth effect. (Continued fixation, stability in the structure of the configuration, etc.) A typically adequate depth effect may, in such cases, be occasioned by objective or subjective labilization (by loosening the fixation and stability through eye-movements, etc.).

2. In contradistinction to these phenomena, images which are

in strict " correspondence " (*i.e.*, without objective disparity) can show a binocular depth effect. Depth comes through the contrast induction of certain parts of the figural situation.

3. Contrast induction can either coöperate with, or work against, the objective " geometrical " disparity.

4. The binocular depth contrast can be measured by means of the contrast stereoscope. It will vary strongly with different observers, but is demonstrable in all cases.

5. The contrast effect depends on (a) the objective disparity of the field which induces the contrast. The greater the disparity, the stronger (within certain limits) will be the contrast. Again, contrast effect depends (b) on the apparent depth of the figure which induces the contrast. The smaller the apparent depth of this figure, the greater will be the contrast effect.

Theory:

1. The " geometrical " theory of retinal correspondence (Hering) must be converted into a dynamic theory.

2. Two points in the retina are in strict correspondence when (a) they are perceptually unified and (b) appear in the plane of fixation (zero-depth, zero-correspondence). Expressed in terms of the dynamic theory: two points are in zero-correspondence when they reveal a maximum stability and immutability after unification. Points which, as a result of a geometrical-anatomical relationship (equal visual angles), are characterized by a " natural " stability, are to be called points of " primary correspondence ".

3. Displacement as the result of a unification of retinal points is the only indispensable perceptual condition for binocular depth. But here, too, displacement must be understood as a dynamic, and not a static, concept. It must be interpreted as the process of change in the spatial values of the retinal points.

4. If two disparate figures are unified, the zero-correspondence within this field is the resultant of at least two factors. The first factor is the " geometrical-anatomical " element of the situation, which tends to establish the zero-correspondence as coincident with the primary correspondence. The second factor is the stability of the binocularly united figure. If the stability

is at a maximum, the displacement is rigid (*i.e.,* it is not a process), and no depth results. The zero-correspondence is shifted to congruent (objectively disparate) points of the figure. The zero-correspondence within such a field varies according to the relative effectiveness of the " anatomical " factor (the primary correspondence) and the factor of configurational stability. Such a field will generally be governed by another type of correspondence, *i.e.,* a " secondary correspondence " and by a concurrent " secondary disparity ".

5. Binocular depth contrast is the perceptual expression of the fact that points of primary correspondence, as a result of the stability tendencies of the frame-figure, become points of secondary disparity. In consequence they experience a secondary displacement (depth effect). The more the secondary zero-correspondence within a binocular field differs from the primary correspondence, the stronger will be the contrast-induction.

Appendix: Hypothesis of Depth

A tentative hypothesis for the purpose of explaining the phenomena of depth is appended. This hypothesis rests on the assumption that, during the process of unification, the movement which is based on the change of width values of retinal points becomes partially transformed into a movement at a place of a constant width value.